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Spectrum for Intelligent Transportation Systems: Allocation and Sharing

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***Abstract*—This paper investigates how much spectrum should be available for Intelligent Transportation Systems (ITS), and whether part of that spectrum should be shared with unlicensed devices, as has been considered by the U.S. Federal Communications Commission (FCC). We found that the ITS bandwidth that maximizes social welfare could be either much more or much less than what has already been allocated, because optimal bandwidth is sensitive to uncertain factors such as device penetration, future data rates, and spectrum opportunity cost. That uncertainty is offset if ITS spectrum is shared. We also found that the bandwidth required to obtain given throughputs on shared spectrum can be considerably less than the bandwidth to obtain the same throughputs in separate bands. We conclude that the spectrum available for ITS should be maintained or increased, but much of ITS spectrum should be shared with non-ITS devices.**

Keywords—spectrum sharing, unlicensed spectrum, Intelligent Transportation Systems, connected vehicles, DSRC, V2X, policy

I. INTRODUCTION

The U.S Federal Communications Commission (FCC) has allocated 75 MHz of spectrum in the 5.9 GHz band for Intelligent Transportation Systems (ITS) since 1999 [1]. This "ITS band" is intended for vehicles that communicate with each other (V2V) and with roadside infrastructure (V2I), which together are referred to as V2X. The FCC adopted the Dedicated Short Range Communications (DSRC) standards for V2X [2]. V2X can support road safety applications such as crash avoidance and non-safety applications such as in-vehicle Internet access [3], [4]. Yet, the question of whether ITS should have an exclusive allocation of 75 MHz is hotly debated. One issue that we address in this paper is how much spectrum should be made available for ITS, rather than other purposes. A related issue that we address is whether the ITS band should be shared with non-vehicular devices. The FCC issued a Notice of Proposed Rulemaking (NPRM) to permit unlicensed devices in that band [5]. However, to date there has been no consensus on the rules to be adopted for such sharing [6].

We address the spectrum issues above by looking into several interrelated research questions. On the issue of how much spectrum to allocate for ITS, we examine the economic benefit of V2X-based Internet access. More specifically, we assume that a certain amount of spectrum is sufficient to serve road safety applications, and then explore whether adding spectrum would result in other benefits. One such benefit could be offloading traffic from cellular onto V2X networks. Previous work has shown that deploying V2X infrastructure for offload is cost-effective in urban areas [7]. This will likely be relevant for the foreseeable future. Although macrocellular capacity continues to increase as carriers expand infrastructure and regulators allocate more spectrum, mobile Internet traffic has grown 18-fold in the past 5 years [8], justifying alternative approaches such as data offload. We have also shown that it is even more cost-effective if infrastructure is shared between Internet access and safety applications [9]. However, those works considered the bandwidth allocated for ITS as fixed and not shared. In contrast, this paper focuses on spectrum management; we examine the economic benefit of adding spectrum to offload Internet traffic. If the marginal benefit of adding one unit of spectrum exceeds its opportunity cost (i.e. the foregone benefit of using that spectrum for something else), then that unit is worth allocating for ITS. With this approach, we estimate the ITS bandwidth that maximizes benefit minus cost. In addition, we examine how that estimate changes with uncertain factors such as data rates of Internet traffic and penetration of V2X devices in vehicles. On the issue of whether ITS spectrum should be shared with unlicensed devices, we address two other research questions. One is what the difference between throughputs to vehicles and unlicensed devices in spectrum exclusively allocated, and throughputs in shared spectrum. Another research question is how much spectrum is needed to carry a given amount of data from vehicles and unlicensed devices when each type of device uses separate spectrum, and how much spectrum is needed to carry the same data if the spectrum is shared.

The debate over the FCC NPRM is primarily about which spectrum-sharing scheme causes less interference to safety-related communications. In contrast, we consider a scenario where part of the ITS band is allocated for safety messages and not shared with other types of communications, but the rest of the spectrum is shared between V2X and unlicensed devices for non-safety communications, on a co-equal basis. (This is consistent with one of the proposals to the NPRM.) In that scenario, Internet Service Providers (ISPs) deploy V2X-based roadside units (RSUs) connected to the Internet to offload part of the growing volume of vehicular traffic. In addition, ITS spectrum allocated for non-safety ITS traffic can be shared with unlicensed devices such as Wi-Fi hotspots.

Our method is based on a packet-level simulation of throughput of vehicular networks and throughput of Wi-Fi

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hotspots representing unlicensed devices. Among the inputs of the simulation that are varied are the amount of spectrum used by vehicular networks and by hotspots. The densities, locations, and data rates of both vehicles and hotspots are also varied. To make this simulation more realistic, many of the assumptions underlying our model come from measurements of an actual, citywide vehicular network operating in Portugal, and the locations of Wi-Fi hotspots in the same city. Besides the analysis of the impact of spectrum sharing on throughput, the simulation results are also used as input to quantify economic benefits and costs for given bandwidths.

TABLE I. ACRONYMS USED IN THIS PAPER

DSRC	Dedicated Short Range Communications
FCC	U.S. Federal Communi-cations Commission
ISP	Internet Service Provider
ITS	Intelligent Transportation Systems
NPRM	Notice of Proposed Rulemaking
NPV	Net Present Value
OBU	Onboard Unit
RSU	Roadside Unit
V2X	Vehicle-to-everything

II. RELATED WORK

To the best of our knowledge, this is the first work that examines whether it is cost-effective to allocate more or less ITS spectrum than what is currently allocated, based on economic marginal benefit and marginal cost of that spectrum.

There is previous research on issues related to sharing of ITS spectrum with unlicensed devices. Such sharing can be done in several ways [10] that include the leading schemes proposed [6], [11] in response to the FCC's sharing NPRM, and other possible arrangements. Previous work mostly examined harmful interference to safety messages on those proposals [1], [12]–[14]. While these works argued that safety applications can be significantly impacted by sharing, some offered regulatory measures for device and protocol improvements to mitigate such interference [12], [13].

Whereas interference on V2X safety has been subject of extensive research and testing, we assumed that safety communications will use dedicated spectrum, and focused our work on the portion that can be shared for non-safety traffic. Some papers investigate issues similar to the ones we do. [15] studied the performance of Wi-Fi devices in the ITS band, using a testbed of two DSRC and two Wi-Fi nodes. They found that both V2X and Wi-Fi performance can degrade with sharing for certain conditions, but changes in protocol parameters and channelization can mitigate such degradation. The work in [16] compared throughput capacity to V2X and Wi-Fi devices among different sharing scenarios, including scenarios of separate spectrum and sharing among equals. They conclude that sharing can result in significant improvement in throughput capacity for unlicensed devices, while causing "acceptable" degradation in V2X performance (in the order of 10% or less). This is related to our work because our investigation of whether to share includes an analysis of throughput performance with and without sharing. However, the research questions, scenarios addressed and contributions are different. First, their assumptions and results are more applicable to DSRC for safety communications, while our work applies to Internet traffic. This is because they consider DSRC nodes broadcasting data, which is typical for safety applications. In contrast, we consider unicast connections over a mesh network formed among vehicles and Internet-connected RSUs, over which TCP connections are established to carry Internet traffic. Second, they assume that the locations of DSRC and unlicensed devices are placed according to Poisson point processes (and the authors show that results differ from those derived from realistic locations), while we derive locations of V2X and unlicensed devices from vehicles, residential hotspots, and road locations from a real city. Another difference is that they use theoretical channel capacity to compare different sharing schemes, each with a fixed amount of spectrum. We instead determine data throughput resulting from existing protocol mechanisms (including e.g. collisions, TCP flow and congestion control), for varying amounts of spectrum, to find the amount of spectrum used in different sharing schemes. Moreover, while their study is relevant to some of the research questions addressed in this paper, we also address questions that previous literature does not, such as how much ITS spectrum to allocate, based on its marginal benefit and cost. Therefore, our work significantly differs from existing research on sharing of the ITS band. This is because in this paper we examine the amount of spectrum to allocate in addition to whatever is necessary for safety, and whether this additional spectrum should be shared.

III. METHOD

To address the research questions we employ an engineering-economic approach, of which a major part is to use packet-level simulation to examine how the ability of vehicular networks and hotspots to carry IP traffic is affected by sharing spectrum between those types of devices. For such an analysis, we adopt the simple measures of performance of throughput to vehicles and throughput to unlicensed devices connected to hotspots, for cases where data rates of incoming traffic, i.e. the total data rates demanded by the devices, are fixed. For this simulation, data from a real vehicular network and Wi-Fi hotspots operating in Portugal is used to define the parameters. Several factors are varied in the simulation to observe the effect on sharing. One factor is the amount of spectrum used, for which we either assume vehicles and hotspots use separate spectrum, or we assume spectrum is shared between vehicles and hotspots, with devices coexisting in a co-equal basis, using 802.11 listen-before-talk mechanisms to mitigate mutual interference. The throughput simulation lets us address the issue of whether ITS spectrum should be shared with unlicensed devices. Other factors that are varied in the simulation include the densities of vehicles and hotspots, data rates of incoming Internet traffic to vehicles and hotspots, and whether hotspots are located indoors or outdoors. Another part of our method addresses the issue of how much spectrum to allocate for ITS. This is done by using the vehicular simulated throughput to estimate the economic benefit of adding ITS spectrum to offload Internet traffic. The model, data used and assumptions are described below.

A. *Model of usage and sharing of the ITS band*

The answers to how much spectrum to allocate for ITS and whether it should be shared depend on benefits accrued by using the ITS band by V2X and unlicensed devices. In this subsection we describe the assumptions regarding the use of the ITS band by those types of devices and what benefits are considered.

The development of V2X and the allocation of the ITS band were motivated primarily by road safety applications. Hence, DSRC standards require that safety-related communications have priority over IP traffic [17]. This requirement was taken into account in the two leading schemes proposed for the FCC NPRM on spectrum sharing [5]. One defining feature of a scheme is whether to allow primary-second sharing or sharing among equals. Another feature of the sharing arrangement is whether devices coexist, or rather actively cooperate to avoid mutual interference [10]. One proposal [6] is based on primary-secondary sharing without cooperation [10] from the primary devices, which means that licensed devices are given priority to use spectrum. Unlicensed devices are allowed to use the same spectrum when and only when their transmissions would not cause harmful interference to DSRC transmissions. In the proposal, unlicensed devices are allowed to use *all channels* of the ITS spectrum, but must stop transmitting in a channel when any DSRC transmission is detected. Supporters of the proposal argue that it doesn't require any change in channel assignments on the ITS band nor in V2X devices, which have already been extensively tested.

The second proposal [11] is based on unlicensed devices being allowed to use only *part* of the ITS band, while the other part is reserved for safety traffic and not shared. In the shared channels, DSRC devices and unlicensed devices would coexist on a co-equal basis, which means that the proposal is not to grant priority access, but rather allow DSRC and unlicensed devices to coexist in shared spectrum through mechanisms such as "listen before talk." Supporters of the coexistent sharing-among-equals proposal argue that it more effectively protects the reliability of safety-related DSRC messages, which would still have a portion of exclusive spectrum allocated.

Like the coexistent sharing-among-equals proposal, in our model safety messages are transmitted exclusively over dedicated channels where no other type of traffic is allowed. We assume those dedicated channels are sufficient to carry all safety traffic, and no additional *safety* benefit is achieved if spectrum is allocated beyond the dedicated channels. (This is consistent with [11], which proposes that three 10 MHz channels in the ITS band be allocated exclusively for safety.) This model allows us to evaluate non-safety benefits from adding spectrum, in a way that is independent from whatever safety benefits are achieved. In our model, using spectrum not dedicated for safety produces the benefit of carrying Internet traffic either to V2X, to unlicensed devices, or both. We assume spectrum is used to carry IP traffic as follows. For the vehicular network, bidirectional connections are established between each vehicle equipped with a V2X onboard unit (OBU) and one fixed RSU which serves as a gateway to the Internet. A vehicle can connect to an RSU either directly or through multiple hops with other vehicles acting as relays, as shown in Fig. 1. Each vehicle uses one channel chosen from a number $D \geq 0$ of channels, while each RSU can use all D channels. Each hotspot uses one channel chosen from either S channels ($0 \leq S \leq D$) that are shared with V2X devices, or $W > 0$ channels located in a separate band.

In our model, vehicles and hotspots coexist in the shared channels. We assume that coexistence is achieved through the listen-before-talk mechanisms specified in IEEE 802.11, the standard used by both unlicensed devices such as Wi-Fi and DSRC devices. We assume coexistence on a co-equal basis, i.e. vehicles and hotspots have equal priority when transmitting.

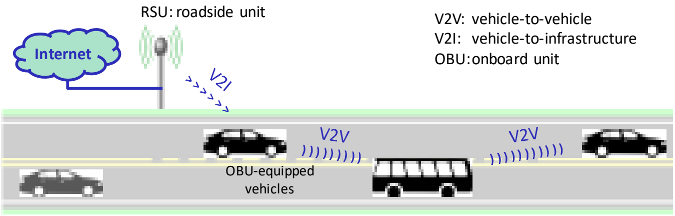

Fig. 1. V2X-based communications with V2V and V2I links. Multiple V2V hops through intermediate vehicles can be used for two endpoints to connect.

We assume that each channel is 10 MHz wide, which is the current channel specification in the ITS band. One channel is used for each hotspot connection, and for each hop in a vehicle-RSU connection. Also, devices choose channels to transmit before establishing the connections. Channels used by vehicles are chosen according to the method proposed in [18], which takes into consideration the expected interference from nodes already assigned to the channels. When a channel is used by either V2X devices only or unlicensed devices only, all interferers are of the same type. When otherwise a channel is shared, interferers can be both V2X and unlicensed devices. For hotspots, one channel is assigned at random per hotspot, with all channels having equal assignment probability.

B. *Economic benefit of ITS spectrum for Internet access*

Our model assumes that a dedicated portion of ITS spectrum provides all safety benefits, and the factor that determines how much spectrum to allocate for ITS is the marginal benefit per MHz of carrying Internet traffic over V2X. We assume that in the absence of V2X networks, in-vehicle Internet access is served by macrocellular networks. Such traffic is expected to increase over time, and infrastructure must be expanded in areas where the cellular network is capacity-limited. However, when Internet traffic is carried over the V2X network at peak hours fewer macrocellular towers are needed than in a scenario without V2X. If the "avoided" cost from fewer towers exceeds the cost of V2X, then deploying V2X devices and spectrum is cost-effective and enhances social welfare when compared to expanding cellular infrastructure. Hence, we define the benefit of offload as the cost savings from deploying fewer cell towers.

Benefit depends on vehicle throughput, and its net present value (NPV) per km^2 is [7] $NPVB = \rho_{savedtowers} C_{tower} \cdot$ C_{tower} is the average NPV per macrocell tower and $\rho_{savedtowers}$ is the total number of towers "saved" per km^2, given by

$$\rho_{savedtowers} = \frac{bpsOff\ FR}{s_{sector}\ bw\ N_{sectors}} \qquad (2)$$

where *bpsOff* is the peak-hour, downstream V2X throughput per km^2, FR is the frequency reuse factor, s_{sector} is the average downstream spectral efficiency in bps/Hz/sector, bw is the total downstream bandwidth per cellular carrier, and $N_{sectors}$ is the number of sectors per tower.

Social welfare is maximized when the marginal benefit per unit of spectrum added equals the marginal costs of offloading [19]. Costs can be of three types. One is the opportunity cost of not allocating the spectrum for a use other than ITS. The opportunity cost is the economic surplus that would be obtained in the best use of the spectrum other than ITS.

The second cost is of RSUs deployed for Internet access. The NPV to deploy RSUs per unit of area is

$$NPVC_{RSU} = c_{RSU} N_{RSU} \quad (3)$$

where c_{RSU} is the cost to deploy a RSU and N_{RSU} is the density of RSUs deployed for Internet access.

N_{RSU} affects not only $NPVC_{RSU}$ but also *bpsOff*, and thus determine benefit. For fixed bandwidth and other factors, we choose N_{RSU} as the RSU density that maximizes $NPVB - NPVC_{RSU}$. The optimal RSU density N_{RSU} is determined for each scenario of numerical assumptions examined in this paper. Moreover, our simulations suggest that in a given scenario the optimal N_{RSU} is approximately insensitive to bandwidth. Hence, we keep N_{RSU} fixed when spectrum amount is varied in a scenario. The modeling of RSUs costs to offload traffic to vehicular networks is described in more detail in [7], [9], [20].

In addition to marginal benefits and costs we also examine average benefits and costs in each scenario. This is because it is possible that for a certain bandwidth marginal benefit equals or exceeds marginal cost, but average benefit does not, since RSU cost is an upfront cost that can be higher than benefit.

The third cost is of OBUs deployed in vehicles. As a base assumption, we consider the case where there is a mandate to equip cars with OBUs for safety, as may occur in the U.S. [21]. In this scenario OBU costs are incurred for safety and thus do not matter for non-safety purposes. (In the results Section we discuss possible implications when a mandate does not occur.)

C. *Opportunity cost of spectrum allocated for ITS*

The cost of spectrum at 5.9 GHz is uncertain, but we can use available evidence to estimate an upper bound. In the case of spectrum allocated for licensed use, a popular way of estimating its opportunity cost is to use the prices paid in license auctions. In recent U.S. auctions, winning bids exceeded \$2 per unit of spectrum per capita (or MHz-pop) for bands in 1.8-2.2 GHz in 2015, which were considerably more expensive than bids that paid around \$0.60 for similar frequencies in 2006 [22]. It must be taken into consideration that physical properties of spectrum make it far less valuable at higher frequencies (e.g. 5.9 GHz) than at lower frequencies [23], [24], perhaps by an order of magnitude. That might place the value of ITS spectrum in the order of a few tens of cents. However, emerging technology operates effectively at higher technology than was typical in the past, so the value of higher frequencies is probably changing, which adds to its uncertainty.

Moreover, current use of Wi-Fi at 5 GHz and the FCC NPRM on sharing indicate that ITS spectrum might be opened for unlicensed use. Estimating the marginal value of unlicensed spectrum is very difficult, but marginal value per MHz would certainly be less than value per MHz averaged over all spectrum. A group of organizations interested in expanding the use of unlicensed spectrum has estimated the total value of spectrum [25], which would average about \$0.70 per MHz-pop. Therefore, the opportunity cost is likely well below this value, perhaps in the vicinity of \$0.20-\$0.40 per MHz-pop.

D. *Simulation model and assumptions*

Our method depends on estimates of throughputs to address the research questions presented in this paper. We simulate throughputs at packet-level from the physical to the transport layer using the ns-3 network simulator [26]. The part of the simulation model that represents vehicles and RSUs is described in greater detail in [7], [9], [20], [27]. We have extended the model to vary the amount of ITS spectrum and to allow sharing with unlicensed devices. Vehicle throughput in an area is defined as the sum, across all OBU-equipped vehicles, of the data throughput achievable between each vehicle and an RSU it communicates with. The network is simulated with vehicles changing positions each 5 seconds. During a 5-s interval, throughput is simulated over a network of non-moving nodes. Then vehicle positions are changed and the process is repeated. Vehicles are positioned according to the GPS logs of buses and taxis over 20 km^2 in Porto, and the positions of cars other than buses are also derived from the GPS logs of taxis.

Steady-state throughput is estimated for each 5-s interval. We assume that half of V2X-equipped cars are exchanging traffic at a constant rate at any given time [7], and any V2X-equipped car can act as relay for others. Each vehicle connects to an RSU through TCP/IP. IP packets are routed through connections with up to three hops. If a vehicle can reach several RSUs through one-hop, then the hop with the least path loss is selected. If all connections have multiple hops, then we select one randomly among the connections with the fewest hops.

Moreover, a hop is used between two nodes only if received signal strength exceeds 15 dB above the sensitivity threshold (-94 dBm). This is the criteria determined empirically in the Porto vehicular network. The transmitted power is 14.6 dBm [28]-[29], and the gains of the transmission antennas are 16 dBi and 5 dBi for the RSUs and vehicles, respectively, which are consistent with Porto settings. The received signal from other vehicles and RSUs is calculated according to the outdoors propagation loss model from [30] (urban microcell B1 variant). The difference between the median simulated loss and the median loss measured in Porto buses is below 5 dB for most distances shorter than 200 meters.

The assumptions for the Wi-Fi traffic are as follows. We adopt the simplifying assumption that all traffic to a hotspot is carried through a single TCP connection between the hotspot and a client device located 10 m away. We consider both indoor hotspots, such as those in residences and offices, and outdoors hotspots, such as those for public Wi-Fi in open locations. For indoor hotspots, we assume that in any given 5-s interval some hotspots are active while others are not. Active hotspots are receiving packets at a constant rate throughout the 5 seconds, while inactive hotspots receive no packets. Every 5 seconds, a different set of hotspots is randomly selected to be active. Moreover, we assume that the density of indoor hotspots in an area depends on population density, and their positions for the simulation are randomly sampled from the set of coordinates obtained from the Wi-Fi provider in Porto (see subsection E below). If the quantity of coordinates to be used in a simulation is higher than the total number of coordinates in the dataset, then the coordinates that exceed the total are also sampled from the same set and shifted as follows. One neighbor hotspot is randomly selected from the three closest neighbors of the hotspot to be shifted. Then its new position is chosen randomly between the original position of the hotspot and the position of its neighbor. This way we obtain samples with desired hotspot density, and with coordinate distribution which intensity approximates that of the original set. We assume all hotspots have a height of 3 m. This overstates the interference where hotspots are far from the ground in multi-story buildings. The signal transmitted by a hotspot is assumed to propagate according to an indoor propagation model [30] to the endpoint of its TCP connection, or a model with wall obstruction with V2X devices or outdoor hotspots.

The assumptions for outdoor hotspots are different. These are placed along the streets of Porto (see E below). In a given street, the inter-hotspot distance is fixed. Signal propagates according to the same outdoors loss model used for vehicles and RSUs. Moreover, we assume that all outdoor hotspots are active at peak hours. The transmission power of all hotspots and their clients is 11 dBm at the antenna output, which is consistent with popular Cisco Wi-Fi hotspots [31].

The number of channels *D* and *S* (or *W*) are defined before the simulation of a 5-s interval is run. Likewise, the selection of the channel used by each node is defined before the simulation.

E. Portugal dataset

To set some of the simulation parameters, we use data (as of March 2015) from a real vehicular network operating in Porto, Portugal, as well as data from Wi-Fi hotspots and the coordinates of roads in that city. Buses equipped with V2X OBUs offer free Internet to passengers, and route data through other buses over multihop connections to reach one of 27 RSUs connected to the Internet. When a vehicle cannot connect to an RSU, data is sent over cellular. We used a dataset with measurements of data transferred over V2X and cellular, and GPS position data of 400+ buses and 400+ taxis. Also, we have collected positions of 65,000+ Wi-Fi hotspots in Porto, which were available in the website of FON, one major Wi-Fi service provider. The dataset includes Wi-Fi hotspots from the subscribers of a major fixed broadband provider in Portugal who partners with FON. Therefore, the data is probably representative of hotspots in households and small businesses. We also use the coordinates of city roads. Porto data is used in four ways. First, GPS positions are used to determine the positions of the vehicles in the simulation. Second, strength of the signal received from RSUs is measured in the buses, and is verified to be compatible with the simulated signal strength in vehicles and RSUs, on average. Third, coordinates of the Wi-Fi hotspots are used to determine the positions of indoor hotspots. Fourth, road locations are used to determine the positions of outdoor hotspots in the simulation as described in D.

F. Base case numerical assumptions

Table II shows the base case numerical assumptions, which are used for the calculation of benefits and costs as defined in III.B. Table III lists the assumed number of vehicles for each population density. These assumptions apply for the results in the following section unless otherwise stated. (For further justification of most numerical assumptions, see [7] and [9].)

Many of the results presented refer to a penetration of V2X OBUs in vehicles of 100%. This is reasonable over the timeframe of a spectrum allocation decision if the Department of Transportation mandates V2X for safety communications [32]. We also examine the impact of lower penetrations on our conclusions, as might be appropriate if no mandate occurs.

Another assumption that is highly uncertain is the data rate per vehicle. We assume a "low" case value of 400 kbps that is consistent with [7], but we also present results for much higher data rates, because data rates have been increasing rapidly over time [33], and future data rates are uncertain.

For other values, we use base assumptions that are representative of five years into the future. Although this work informs spectrum allocation decisions that may span decades, the rate of technological change and adoption in wireless communications make decade-long predictions highly uncertain. Since five years is a typical horizon for predictions about Internet usage for given technologies (see e.g. [33]), we adopted five years as our horizon for analysis.

The base assumption for the average data rate of incoming Internet traffic in the peak hour over active hotspots is 5 Mbps in five years. This value is reasonable because it has been found that the majority of traffic in the U.S. is currently from video applications [34]. Typical video streams have an average bitrate of 2 Mbps ([35], Netflix HD encoding), which we assume as today's average peak-hour data rate per active hotspot, and usage for fixed broadband subscribers is forecast to grow at roughly 19% per year [33].

For indoor hotspots, we assume that 15% of hotspots will be active at a time. This is reasonable because current estimates for the average traffic in U.S. households are currently around 100 GB per month [36], [33], [34]. A hotspot transferring 300 kbps at all times would transfer 100 GB over a month, then the share of active hotspots is assumed as 300 kbps / 2 Mbps = 15%. Although this assumption about the share of active hotspots at a given time several years into the future is uncertain, it is likely that not all active hotspots would be using the channels in the ITS band in any given time. Hence, this assumption may result in conservative results, given that the real interference from indoor hotspots may be lower than what we estimate.

For outdoor hotspots, we assume they to be placed every 150 m in all urban roads. Since deployment of outdoor Wi-Fi has been limited to downtown areas of a few cities and other sparse locations, this assumption is also likely to result in higher interference to vehicles than in typical urban areas. (For this reason, we compare scenarios with both indoor and outdoor hotspots with scenarios with indoor hotspots only.)

TABLE II. BASE CASE ASSUMPTIONS (SEE [7], [9] FOR DETAILS)

Assumption	Value
Discount rate	7%, real
Time horizon for analysis	5 years
Data rate of incoming Internet traffic per vehicle on the road	Low scenario: 400 kbps average - 50% of cars are endpoints for 800 kbps, 50% are relays only High scenario: 4 Mbps average
Share of downstream traffic	90% of data from RSU to vehicle
Macrocellular spectrum efficiency s_{sector}	1.4 bps/Hz/sector (downstream average)
Sectors per macrocell $N_{sectors}$	3
Macrocellular bandwidth bw	70 MHz (downlink per cellular carrier)
Reuse factor FR	1 (macrocellular frequency reuse)
Unit cost of macrocellular tower C_{tower}*	$750,000 (see e.g. [37]): NPV of capital and operating expenses (Capex and Opex) over time horizon
Cost of one V2X Internet-only RSU c_{io}*	$14,000 (NPV of Capex and Opex over time horizon)
Population density	5,000 people/km^2
Indoor hotspots per capita	1 hotspot for every 4 people (see section D) [8]
Outdoor hotpot locations	Placed along roads every 150 m [38]
Data rate of incoming Internet traffic per hotspot	Low scenario: 5 Mbps at 15% of hotspots at each 5-s interval (see below) High scenario: 27 Mbps

* Monetary values in 2014 U.S. dollars

TABLE III. NUMBER OF VEHICLES ON THE ROAD AT PEAK HOURS, AS A FUNCTION OF POPULATION DENSITY [20]

Population	Vehicles owned		Vehicles on the road at peak hours	
per km^2	per capita	per km^2	per capita	per km^2
200	0.75	150	0.04	8
1000	0.65	650	0.04	40
2000	0.6	1200	0.04	80
3000	0.6	1800	0.04	120
5000	0.46	2300	0.04	200
12000	0.24	2900	0.033	400

IV. RESULTS

In this section, we first address the issue of how much spectrum to allocate for ITS, by estimating benefits and costs. We then address the issue of whether the ITS band should be shared with Wi-Fi devices. The throughput for each scenario of bandwidth, device density and data rates is derived by averaging throughput for at least 1000 vehicles. Assuming that the throughputs of the vehicles are mutually independent, then the 95% confidence interval is within 10% of the mean throughput.

A. How much spectrum to allocate for ITS

To address the issue of how much spectrum to make available, in this subsection we estimate economic benefits and costs of deploying V2X infrastructure for internet access on a nationwide scale for the U.S. For this estimate, we assume spectrum is used for ITS only, i.e. it is not shared with unlicensed devices. We then use benefits and infrastructure costs to derive the bandwidth that maximizes social welfare as a function of uncertain factors such as the opportunity cost of spectrum in the ITS band, data rates, and OBU penetration.

We quantify economic benefits and costs of allocating a given amount of spectrum for ITS throughout the entire nation, even in regions where population density does not justify V2X networks (i.e. for those locations there is no benefit but there is a cost of spectrum), because this is generally how spectrum is allocated. We calculate benefits and costs of using the spectrum for ITS in each U.S. census tract and then sum benefits and costs over all tracts. We assume that RSU deployment decisions are made at the census tract level, i.e. the optimal quantity of RSUs N_{RSU} to deploy (or not) for Internet access (see III.B) is determined at each census tract based on its average population density (this approach was also employed in [37], [39]).

Fig. 2 shows marginal and average benefit minus RSU cost (B-C) per MHz-pop on a nationwide scale for the U.S., as a function of bandwidth allocated exclusively for vehicles. The graph shows results for two data rates of incoming Internet traffic per vehicle (low and high scenario as in Table II). The other assumptions are base case values. For a particular bandwidth to be worth allocating, both marginal and average benefit minus RSU cost B-C must exceed the opportunity cost of ITS spectrum [19]. If marginal benefit minus cost is less than opportunity cost at bandwidths where the former is decreasing, then reducing bandwidth increases benefit minus cost. If average benefit minus cost is less than opportunity cost, then benefit minus cost is greater with a bandwidth of 0.

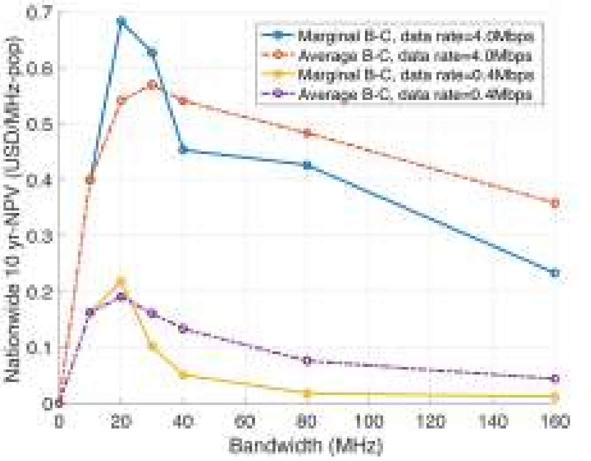

Fig. 2. Nationwide benefit minus RSU cost per capita (B-C), as a function of bandwidth. Lines for two different data rates of incoming traffic per vehicle are shown. OBU penetration is 100%.

Fig. 2 shows that benefit minus RSU cost does not change monotonically with bandwidth. This is because while marginal and average benefit do decrease monotonically with bandwidth, RSU cost does not. It is proportional to the number of RSUs deployed in an area – see Eq. (3). We found that the quantity of RSUs deployed is roughly invariant with bandwidth, for the range of data rates, densities and other factors we considered.

Given the uncertainty in the opportunity cost of ITS spectrum (see III.C), we examine the relationship between the opportunity cost and the optimal bandwidth in Fig. 3. For a given opportunity cost, the graph shows the maximum bandwidth for which marginal and average benefit minus RSU cost exceed that opportunity cost. In III.C we conjecture that the cost of ITS spectrum might be around $0.20-$0.40 per MHz-pop. Fig. 3 shows that for such a range of opportunity cost it might be worth allocating spectrum, but the amount that maximizes social welfare depends not only on spectrum cost but also on other factors as well, such as data rates. For example, at an OBU penetration of 100% of vehicles and average data rate of incoming traffic of 4 Mbps per vehicle, Fig. 3 shows that it is worth allocating 40 MHz of ITS spectrum, which is the bandwidth currently available for non-safety use, as long as the opportunity cost of spectrum is below $0.45 per MHz-pop. However, for a lower average data rate of 0.4 Mbps per vehicle the same bandwidth could be allocated only if the opportunity cost is much lower (below $0.05 per MHz-pop). From Fig. 3 we see that there are realistic scenarios in which it is worth allocating more spectrum than it is currently available for non-safety use, but there are also scenarios in which it is worth allocating less, if any.

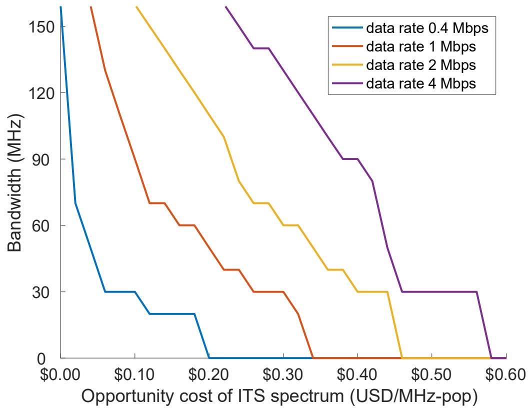

Fig. 3. Bandwidth that maximizes social welfare (on a nationwide basis), as a function of the opportunity cost of spectrum in the ITS band. Curves are shown for distinct data rates of incoming traffic per vehicle. OBU penetration is 100% and other numerical assumptions are in base case values.

Moreover, the results above are for an OBU penetration of 100%, which is consistent with a mandate of V2X in all vehicles. Out of the context of a mandate, lower penetrations are possible, with OBUs being deployed more frequently in vehicles that demand higher data rates. Fig. 4 shows the bandwidth that maximizes social welfare in such a scenario. The graph shows that bandwidth is highly sensitive to penetration. The range of opportunity costs that results in any bandwidth to be allocated is significantly smaller in Fig. 4 than for the scenarios with 100% penetration (Fig. 3). However, Fig. 4 shows that a small increase in penetration (5% to 10% in the graph) changes significantly the bandwidths worth allocating, especially if the opportunity cost of spectrum is in the order of tens of cents per MHz-pop as discussed in III.C. For example, at 10% penetration it is worth allocating 40 MHz (the bandwidth currently available for non-safety use) if the cost of spectrum is about $0.18 per MHz-pop. However, a scenario where it is not worth allocating spectrum in excess of safety is also plausible, especially for low OBU penetrations and/or if spectrum is valued at more than a few tens of cents per MHz-pop.

It is important to note that this discussion applies for spectrum allocated exclusively for ITS. While we found that the bandwidth that maximizes social welfare depends on the uncertainty of its opportunity cost and other factors, our estimates of benefit do not capture the value of sharing spectrum with unlicensed devices. Benefits of sharing are discussed in the following subsection.

B. *Should ITS spectrum be shared with unlicensed devices?*

To address the issue of whether to share spectrum, in this subsection we estimate throughputs to vehicles and unlicensed devices when different types of device uses separate channels, and examine how those throughputs differ when the devices use shared spectrum. In addition, we show the amount of shared spectrum needed to achieve given throughputs, and compare to the total amount of spectrum in separate bands to achieve the same throughput.

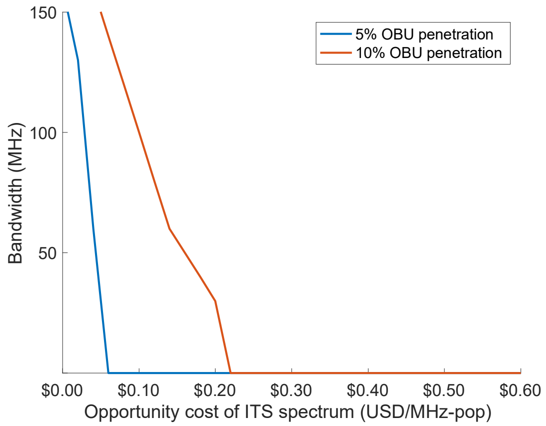

Fig. 4. Bandwidth that maximizes social welfare (on a nationwide basis) as a function of the opportunity cost of spectrum in the ITS band. Curves are shown for distinct penetrations of OBUs. Data rate per OBU is 27 Mbps (the maximum for 802.11p in a 10 MHz channel) and other numbers are at base case values.

Fig. 5 and 6 show vehicle throughput and hotspot throughput. In both graphs the horizontal axis is the bandwidth allocated (in excess to what is used by safety). We show throughputs for indoor hotspots only (*I* in the legend) and indoor+oudoor hotpots (*IO*), for a “low” and a “high” scenarios of population densities (*pop*), OBU penetration (*pen*) and data rates of incoming traffic per OBU. Other assumptions are fixed at base case values. As expected, throughput increases with spectrum bandwidth for both vehicles and hotspots, although at a diminishing rate. As throughput approaches the incoming data rate, adding spectrum adds little, if anything, to performance.

The graphs also show how throughputs change with sharing. Fig. 5 suggests that the difference between throughput to vehicles on exclusive spectrum and throughput on shared spectrum can be negligible in some scenarios and significant in others. We examined the difference between throughputs for scenarios spanning a wide range of assumptions. We varied population density from 1,000 to 20,000 people per km^2, OBU penetration from 25% to 100%, data rates of incoming traffic varying from 400 kbps per vehicle and 5 Mbps per hotspot to 4 Mbps per vehicle and 27 Mbps per hotspots, and with outdoor hotspots either being present or not. For these scenarios (not all are shown in Fig. 5), vehicle throughput on channels shared with hotspots can be up to 30% lower than vehicle throughput on exclusive channels in some scenarios (e.g. when outdoor hotpots are present). In other scenarios, the difference can be smaller.

Fig. 6 suggests that the difference between hotspot throughput in separate spectrum and in shared spectrum is small. For all scenarios simulated the difference is less than 10%, which is mostly within the 95% confidence interval, and is well below that value for most scenarios.

The impact of sharing on vehicular network throughput and on hotspot throughput is probably small because most vehicles are not close enough to a hotspot to experience or cause harmful interference at any given time. The densities and data rates of hotspots may be much higher than that of vehicles, but many of them are indoors, which are separated from streets by walls.

We also look into how much spectrum is needed to carry a given amount of data from vehicles and unlicensed devices over separate channels, and how much spectrum is needed to carry the same amount of data on shared spectrum. We determine those amounts of shared and separated spectrum as follows. First, we find the vehicle throughput and the hotspot throughput for a given amount of shared spectrum. Then, we find the amount of spectrum used to achieve that same vehicular throughput, but on spectrum used by vehicles only. Likewise, we find the amount of spectrum used by hotspots only. The process is repeated for several vehicular and hotspot throughputs.

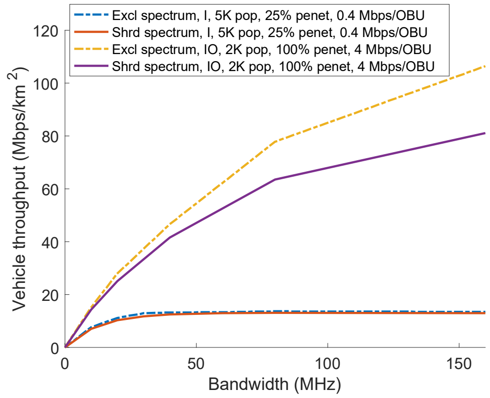

Fig. 5. Vehicle throughput as a function of spectrum allocated. The dashed lines are for spectrum used for vehicles only, while the solid lines are for vehicles and hotspots on shared spectrum.

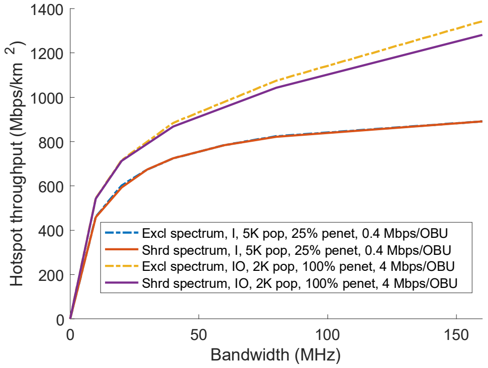

Fig. 6. Hotspot throughput as a function of spectrum allocated. The dashed lines are for spectrum used for hotspots only, while the solid lines are for vehicles and hotspots on shared spectrum. (The curves for I, 5K, 25% 0.4 Mbps mostly overlap.)

Fig. 7 shows the amounts of spectrum obtained with the procedure above as a function of vehicle and hotspot throughputs. The graph is for a population density of 2,000 people per km^2, which is representative of a city like Pittsburgh. Data rates are of the "high" scenario, and OBU penetration and other assumptions are in the base case values described in III.E. In Fig. 7, one curve is the total amount of spectrum when vehicles and hotspots use spectrum separately, and the other is the amount of spectrum when it is shared. The horizontal axis represents vehicle throughput and the colors represent hotspot throughput. The curves for any given vehicle throughput also refer to the same hotspot throughput (i.e. the curves at any given vehicle throughput have the same color).

For the scenario described, Fig. 7 shows that almost twice as much spectrum is needed when that spectrum is allocated in separate bands for vehicles and hotspots, when compared to all devices using shared spectrum. Therefore, the graph shows that it is possible to obtain the same performance for vehicles and hotspots using significantly less spectrum when it is shared, compared with vehicles and hotspots using separate spectrum. The graph also shows that there is a limit for the vehicle throughput that cannot be exceeded because Fig. 7 is derived from a fixed data rate of incoming traffic. As throughout approaches that rate, additional spectrum does not improve throughput, regardless of whether that spectrum is shared or not (as shown in Fig. 5 and 6).

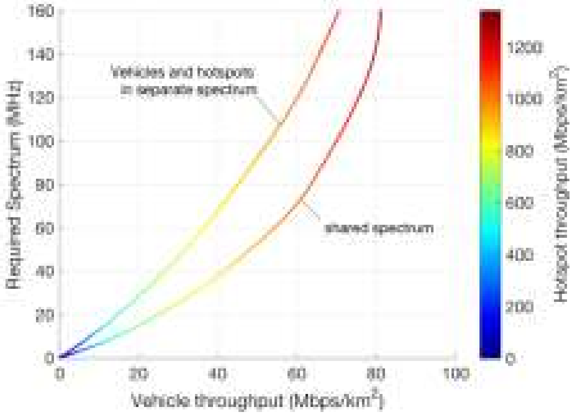

Fig. 7. Required spectrum to achieve given vehicular and hotspot throughputs, as a function of vehicular throughput. Points of equal color refer to equal hotspot throughput. Colors are coded in the bar (right).

We found that less shared spectrum is required for other scenarios as well, when compared with vehicles and hotspots using separate spectrum. In Fig. 8 we show the ratio of the total amount of spectrum used by vehicles and hotspots in separate bands, to the amount of spectrum with both types of devices using shared channels. The bars show the ratio scenarios with indoor hotspots only (*I* in the figure) compared with indoor and outdoor hotspots (*IO*), population densities varying from 1,000 to 20,000 people per km^2, OBU penetration from 25% to 100%, and data rates of incoming traffic from 400 kbps per vehicle and 5 Mbps per hotspot to 4 Mbps per vehicle and 27 Mbps per hotspot. For adjacent bars, one factor is varied at a time.

The graph is useful to show both the absolute magnitude of the ratios, and the difference between ratios. Fig. 8 shows that all scenarios examined have average bandwidth ratio greater than 1, meaning that shared spectrum uses less bandwidth than separate spectrum to achieve given throughputs, for numerical values that are likely representative of the relevant ranges of assumptions. (However, for some scenarios the 95% confidence interval for the ratio suggests that the ratio can be a low as 0.75, for lower population densities and when throughput is close to the maximum achievable in the scenario.)

In particular, the graph shows that a scenario with indoor-only hotspots has a higher ratio than a similar scenario but with indoor and outdoor hotspots. This means that more spectrum is needed to achieve given throughputs when there are indoor and outdoor hotspots in shared spectrum, because of the increased interference. Comparison between indoor-only and indoor-outdoor hotspots for other scenarios of population density, penetration and data rates confirm that trend (these are not shown in Fig. 8).

Fig. 8 also shows that the ratio of bandwidth increases with data rates of incoming traffic to vehicles and hotspots. This suggests that it is worth sharing spectrum for a variation in data rates of an order of magnitude. Even if that data rates increase sharply in the future, sharing appears to be beneficial.

The bottom bars show that the ratio is similar for different population densities or OBU penetrations. The differences in ratios are not statistically significant at a 5% confidence level. However, as with most other scenarios the ratio is close to 2, which means that sharing spectrum requires as much as half the bandwidth required to achieve given throughputs in separate bands.

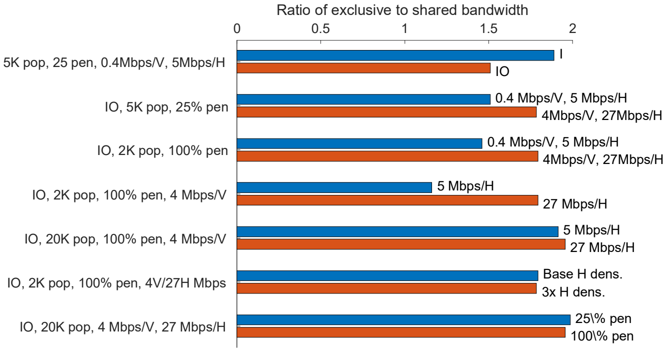

Fig. 8. Ratio of bandwidth in exclusive channels to bandwidth in shared channels to achieve a given target throughput. The target vehicle throughput in each scenario is set as half the throughput obtained at 160 MHz. Each bar shows the ratio for a different scenario. The pairs of bars compare ratios for scenarios where one factor being is changed at a time: Indoor hotspots (I) vs Indoor and outdoor (IO), data rates (Mbps/V for vehicles, Mbps/H for hotspots), hotspot density (pop+pen), and vehicle density (pen).

V. CONCLUSIONS

In this paper, we address the issues of how much spectrum should be available for ITS, and whether that spectrum should be shared with unlicensed devices, as has been proposed by the FCC and others. For that analysis, we considered the scenario in which safety messages are transmitted over spectrum that is not shared for other types of communications, while V2X and unlicensed devices coexist in shared spectrum in a co-equal basis to carry non-safety-critical information such Internet traffic. (This is consistent with proposed uses of the ITS band such as [11].)

We found that if spectrum is allocated exclusively to ITS, there are realistic scenarios where allocating spectrum far in excess of what is used for safety enhances social welfare, and there are also realistic scenarios where too much spectrum has already been allocated for ITS. The bandwidth that maximizes social welfare is sensitive to uncertain factors such as the penetration of devices in vehicles, data rates (particularly those to unlicensed devices), and the opportunity cost of 5.9 GHz spectrum. For example, in scenarios of higher data rates and penetration, adding 40 MHz enhances social welfare if the opportunity cost is about $0.45 per MHz-pop or less. On the other hand, if data rates of Internet traffic and penetration of devices in vehicles does not reach the levels assumed, then it might be that it is not cost-effective to allocate any spectrum in excess to what is allocated for safety. Because of this uncertainty, allocating spectrum exclusively runs the risk of not providing enough spectrum for welfare-enhancing ITS.

This uncertainty becomes less problematic if ITS spectrum is shared. Moreover, we found that it is highly efficient to share spectrum allocated for ITS with unlicensed devices. We have found that vehicles and unlicensed devices using separate bands might require 50-100% more bandwidth than is required to achieve the same average throughputs in shared spectrum. This is true for most scenarios that we believe represent the relevant range of population densities, penetrations of vehicular devices and data rates of Internet traffic, and whether unlicensed devices are located indoor or outdoors. While sharing is spectrally efficient when usage of V2X and unlicensed devices are predictable, it is even better in the scenarios where data rates and/or penetration are much lower than expected due to the uncertainty discussed above, because even if spectrum being added exclusively for ITS might not be justified, shared spectrum is still well used by unlicensed devices.

In the recent policy debate over ITS spectrum, it has generally been assumed that the size of the ITS band would remain fixed at its current level, and the question is whether to share with unlicensed devices. If the bandwidth available to vehicles is fixed, we have found that the throughput achievable in shared spectrum can be lower than the throughput in exclusive spectrum (up to 1/3 lower, depending on the scenario). However, there is no reason why the bandwidth of the ITS band cannot be increased if we allow unlicensed devices to share the ITS band. If spectrum policymakers wish to give V2X better throughput than they could achieve in the existing ITS band after unlicensed devices are allowed to share, then policymakers could change regulations to increase the size of the ITS band while still giving unlicensed devices access. In other words, while unlicensed devices gain access to the ITS band, V2X devices could use the adjacent unlicensed band for non-safety-critical traffic. (Again, sharing the ITS band might exclude the portion of the ITS band reserved for safety messages.) Under these circumstances, vehicles and unlicensed devices would achieve the same throughput performance in shared spectrum while using less bandwidth overall. Besides, we have found the throughput to unlicensed devices in shared spectrum to be not significantly lower than in exclusive spectrum. Therefore, sharing spectrum allocated for ITS with unlicensed devices effectively represents extra bandwidth for those devices, without compromising their throughput performance.

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