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Throughput and Economics of DSRC-Based Internet of Vehicles

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ABSTRACT Vehicular mesh networks could be an important new way to provide Internet access in urban areas using dedicated short range communications (DSRC). In some circumstances, DSRC technology is more cost-effective than expanding the capacity of cellular networks. We determine what those circumstances are by combining our simulation model with data collected from an actual vehicular network that is operating in Portugal. We use the model to estimate how much Internet traffic can be offloaded to vehicular networks that would otherwise be carried by cellular networks, under a variety of conditions. We use offloaded traffic to estimate the benefits of cost savings of reduced cellular infrastructure due to offload, and the cost of the DSRC vehicular network to carry that traffic. Then, we determine when benefit exceeds cost. We find that the benefits from the Internet traffic alone are not enough to justify a universal mandate to deploy DSRC in all vehicles, i.e., the benefits of Internet access alone are less than total costs. However, the majority of DSRC-related costs must be incurred anyway if safety is to be enhanced. Thus, soon after a mandate to put DSRC in new vehicles becomes effective, the benefits of Internet access through vehicular networks in densely populated areas would be significantly greater than the remaining costs, which are the costs of roadside infrastructure that can serve as a gateway to the Internet. Moreover, the benefit of Internet access would exceed DSRC infrastructure cost in regions with lower and lower population densities over time.

INDEX TERMS Benefit-cost analysis, dedicated short range communications, DSRC, mobile data offload, mobile Internet, social welfare, vehicular networks.

I. INTRODUCTION

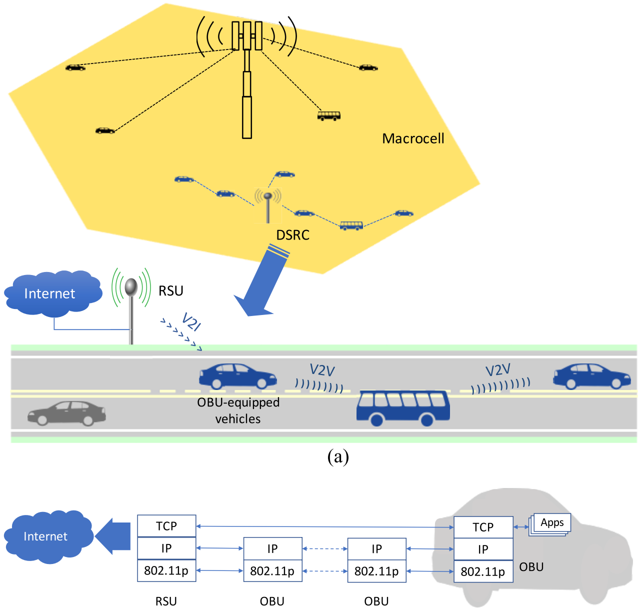
Vehicular DSRC mesh networks can run Internet protocols such as IP, with routers placed in automobiles and in infrastructure near roads. DSRC technology may soon be widely deployed, primarily as a way of enhancing automotive safety [1]–[3]. This paper investigates an entirely different use of vehicular networks – to provide Internet access, especially for mobile devices.

There is motivation to find new cost-effective approaches as Internet traffic over mobile networks has been growing [4]. Cisco forecasts a sharp increase in mobile traffic over the coming years [5]. Expanding capacity of cellular networks to meet such traffic growth would require significant spectrum, capital, or both. However, if part of the traffic could be offloaded from the macrocellular networks to alternative networks, then the growth in traffic demand might be met while adding fewer new macrocells.

This paper shows that under some important circumstances, vehicular networks can provide Internet access at lower costs than would be incurred in today's cellular networks. The paper analyzes the costs and benefits of using DSRC technology. The development of DSRC is primarily motivated by road safety applications rather than Internet access. The U.S. Department of Transportation (DOT) has proposed rulemaking in 2016 to mandate DSRC onboard units (OBUs) in new vehicles [6], and the U.S. Federal Communications Commission (FCC) has already allocated 75 MHz of spectrum for Intelligent Transportation Systems (ITS) [1], [7]. The DSRC standards allow part of the ITS spectrum to be used for applications other than safety [1], [8], [9], with safety messages having higher priority than other communications to avoid harmful interference to the former. Examples of applications that involve non-safety communications include Internet access [9], [10].

We do a cost-benefit analysis that will inform important decisions regarding whether resources should be invested in vehicular networks for Internet access, rather than just vehicular safety. One decision is whether to invest in roadside units (RSUs) for Internet access. We find that deployment of RSUs in dense urban areas is likely to increase social welfare fairly soon after a mandate to put onboard units (OBUs) in vehicles becomes effective. Moreover, we find that deployment will increase social welfare in less densely populated areas over time, as the penetration of DSRC in vehicles and data rates increase. Other decisions include whether to allocate spectrum and mandate OBUs in the first place, if these steps are not taken for safety reasons. In situations in which benefit of Internet access exceeds all types of DSRC cost, then social welfare is increased by mandating DSRC devices in all vehicles and allocating spectrum regardless of whether there are benefits other than Internet access. This paper will also determine if this is the case.

Our estimates of benefits and costs of Internet access over DSRC depend on the achievable throughput of the vehicular network. Hence, we are interested in determining how throughput depends on the density of vehicles and RSUs, and data rates of incoming traffic. Moreover, we examine how throughput scales as those factors increase over time.



(a)

(b)

FIGURE 1. Scenario of vehicular Internet access considered in this paper. (a) Vehicular communications through heterogeneous networks (cellular and DSRC). (b) Model of DSRC-based connection between an RSU and a vehicle equipped with an OBU.

We consider the heterogeneous DSRC and macrocellular networks represented in Fig. 1 (a). In this scenario, OBU-equipped vehicles are capable of connecting to the Internet in two ways. One is through macrocells. The other way is through DSRC mesh networks comprised of multihop paths. These paths are formed by vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links. Those links connect vehicles to RSUs that serve as gateways to the Internet. Safety messages and Internet packets are sent over separate DSRC channels. Therefore, in this scenario there is no interference between safety and Internet traffic.

Our methodology combines a packet-level simulation model with data collected from an actual vehicular network operating in Porto, Portugal. The first step is to estimate how much vehicular Internet traffic, which would otherwise be carried by macrocells, can instead be carried by a DSRC-based network under different conditions. To achieve this, we simulate the data rate transferred between vehicles and RSUs. Our simulation employs realistic representations of the elements of a network that greatly affect throughput, including the location of vehicles and RSUs, the signal loss between devices, and the DSRC protocol itself. Some of that realism comes from measurement data taken from the city-scale trial in Portugal. For example, our models of vehicle traffic patterns are based in part on location data collected from over 800 buses and taxis.

The next step is to estimate costs and benefits. Today, nearly all mobile traffic must be carried over a macrocell tower. In a capacity-limited cellular network, a reduction of traffic from mobile devices in the busy hour allows each cell to provide adequate capacity over a larger area, thereby reducing the number of towers needed to cover a given region. We define the benefit of Internet access through vehicular networks as the cost savings from reducing the number of towers. This is compared to the costs of DSRC RSUs, spectrum or OBUs, under a wide range of values for factors such as population density, penetration of DSRC in vehicles, data rate per DSRC-equipped vehicle, and unit costs.

This paper is organized as follows. Section II describes previous research and how our work is positioned. Section III describes the DSRC network in Porto for Internet access, and which data is used from it. Section IV explains the simulation, the benefit-cost analysis and their underlying assumptions. Section V contains the results, and Section VI ends the paper with the conclusions, limitations and opportunities for future work.

II. RELATED WORK

Previous work discussed issues related to vehicular communications over heterogeneous networks. In the survey, Hossain *et al.* [11] predicted that ubiquitous deployment of DSRC may take decades, and therefore OBUs that switch between DSRC and cellular are possibly cost-effective solutions. In this paper, we examine the actual conditions under which DSRC is cost-effective when compared to cellular, by quantifying the economic benefits and costs of offloading cellular traffic through DSRC. Other work focused on specific technical issues such as the method to select among heterogeneous networks [12], [13]. In contrast, we determine the locations where it is cost-effective to offload traffic from cellular, and would constitute a choice between heterogeneous networks. That is, we assume that DSRC networks for Internet access will be deployed only where they are cost-effective, and then we quantify benefits and costs at those locations. (We also assume that QoS will be satisfied by whatever network that is selected.)

There is extensive work on the technical capabilities (e.g. [1], [3], [8]–[10]), and economic benefits and costs of DSRC for safety communications [6]. However, to our knowledge there has been little work on the cost-effectiveness of vehicular communications over heterogeneous networks for non-safety applications. The leading exception [14] compared costs of various architectures when deploying greenfield infrastructure that would provide ubiquitous coverage in a given region using a given 10-MHz block of spectrum. This is related but different from the scenario we address, in that we assume that cellular carriers already provide ubiquitous coverage in cellular spectrum, and the question is whether it is more cost-effective to expand existing cellular carriers or deploy infrastructure for vehicular networks in DSRC spectrum.

In [14], they compare three types of infrastructure: cellular towers that provide macrocells, ''roadside access points'' that provide microcells, and mesh networks. For each type, direct communications between mobile devices and infrastructure is supplemented with V2V vehicular communications if and only if the infrastructure density is insufficient to provide ubiquitous coverage. In these cases, the authors assume that there will be enough vehicles to cover all gaps in coverage. For each type of infrastructure, lower bounds of throughput capacity are derived as a function of infrastructure density, and costs are compared for a fixed capacity. When the desired capacity is low, they conclude that roadside microcells are less cost-effective than macrocells and mesh infrastructure. However, if the desired capacity is higher they conclude that roadside microcells are more cost-effective than macrocells. This is a somewhat surprising result from [14], considering that current greenfield deployments for mobile Internet service typically start with macrocells rather than microcell or mesh infrastructure.

The findings in [14] are in part the result of assumptions that are somewhat different from those of this paper. For example, they assume that macrocellular networks have a frequency reuse factor of 9, and no cell sectorization. In contrast, we assume a reuse factor of 1 and 3 sectors per cell, as we might expect in an urban LTE deployment. They assume that either cellular or vehicular networks would operate in the same 10 MHz block. In contrast, we assume that cellular carriers operate in 70 MHz of spectrum as is typical for a large provider, and vehicular networks operate in 40 MHz of spectrum at a much higher frequency in accordance with FCC regulations. Lu *et al.* [14] assume frequency reuse can be managed so that there are no packet collisions, even in a vehicular network which can have hidden terminals. To take the impact of collisions into account, as well as congestion, we use packet simulation with protocols and parameters consistent with the DSRC, IP and TCP standards.

Some carriers and researchers are considering the use of fixed Wi-Fi hotspots that offload vehicular data traffic that is tolerant to delays [15]–[21]. Moreover, there has been research on the resulting economic impact [22], [23] of Wi-Fi offloading. However, vehicular networks offer new opportunities for Internet access that are quite different from what is possible with Wi-Fi hotspots, and this requires new analysis.

The benefits of vehicular networks are different from Wi-Fi hotspots because the traffic carried is different. Wi-Fi is often a good solution for users who are stationary for the period when they are accessing the Internet, but it is often inadequate for users who access the Internet while moving [24]. In addition, the costs associated with vehicular networks are quite different from the costs of typical Wi-Fi networks, which are generally microcellular. In a DSRC-based mesh network as illustrated in Fig. 1, a relatively small number of RSUs can connect a large number of vehicles equipped with OBUs to the Internet. It also helps that DSRC links can be longer than typical Wi-Fi hotspots, i.e. up 250-350 meters in cluttered urban areas (as measured in Portugal). Although far fewer fixed devices are needed to cover an area with a vehicular network than with Wi-Fi, those fixed DSRC devices are also more expensive, because they must operate outdoors in hostile conditions, and they are not currently mass produced. Because of these differences, this paper is important as it examines the cost effectiveness of DSRC-based mesh networks to offload Internet traffic.

III. PORTO VEHICULAR NETWORK AND DATASET

Porto is the second largest city in Portugal [25]. In September 2014, its urban bus authority started offering free Wi-Fi service for passengers in 400+ buses that have OBUs equipped with a Wi-Fi hotspot. Each bus OBU also has a router that relays traffic to/from the Internet through one of two possible paths. The preferred is through the use of DSRC, for which there were 27 RSUs (as of March 2015) deployed at fixed locations of the city; buses can connect to RSUs either directly or through multihop connections using other buses. If no DSRC path is available, then data is transferred over LTE.

As of March 2015, over 2.7 TB/month were transferred. The observed volume transferred through DSRC varies with location, with the majority of the RSUs being concentrated in downtown, where the offload ratio of bytes transferred through DSRC to the total number of bytes can reach as much as 70% at peak hours.

Taxis are also equipped with devices that collect data. Of the city estimated total of 800 taxis, GPS positions of 400+ vehicles were collected during one month in 2012.

The data from Porto buses and taxis that were used in this paper are summarized in Table 1.

TABLE 1. Data used for the analysis.

Data from busses from October 2014 to March 2015 and from taxis in March 2012		
Data Item	Number of Observations	Description
Data volume/ position/signal per 15-second per bus	400+ buses: 240×10^6 data points	Per 15-second interval, per bus GPS position, received signal strength from RSU (if V2I-connected) or peer bus (if V2V-connected)
RSU positions	27 RSUs	Per RSU: GPS position and height
Position per second per taxi	400+ taxis: 120×10^6 data points	Per second, per taxi: time, GPS position, and an identifier of the vehicle

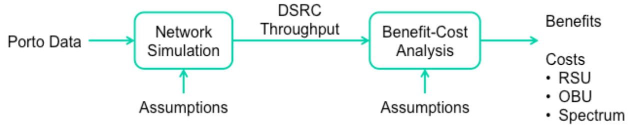


FIGURE 2. Summary of steps, inputs and outputs of the methodology.

IV. METHODOLOGY

In this paper, we employ a two-step method. The first step is to evaluate the throughput to DSRC-equipped vehicles using network simulation, in several scenarios. The second step is to use those throughputs to estimate benefits, and costs of Internet access through vehicular networks. The two-step method is illustrated in Fig. 2 and described in Subsections IV.A and IV.B.

Porto data is used in two ways: first, bus and taxi GPS positions are used to determine the positions of the vehicles in the simulation of a vehicular network. Second, the received signal measured in the buses is used to verify whether the simulated signal loss is compatible with measured loss, on average. The two-step method also uses other parameters such as the number of vehicles, and data rates per DSRC-equipped vehicle. The numerical assumptions chosen for the base case scenario and its variations are described in Subsection IV.C.

Our engineering-economic approach is based on network simulation and benefit-cost analysis, which are methods that have been employed extensively in previous work. While research such as [14] employed analytical methods to derive throughput to vehicular users, we have opted for packet-level simulation as it lets us use data from the real network in Porto to represent vehicle densities more realistically. As for the simulation platform, we have chosen ns-3, which has been used for research on wireless networks [26], [27]. Moreover, simulation lets us observe the impact of varying conditions such as data rates and densities of vehicles and RSUs. It would be impossible or impractical to vary those conditions in a real network such as that of Porto. Regarding economic analysis, previous research such as [14] compared costs of greenfield deployments of different infrastructures, which is an approach that does not apply to locations already served by cellular networks. In contrast, we used benefit-cost analysis to quantify the *net* economic impact of deploying DSRC networks to offload traffic from existing cell towers. Moreover, benefit-cost analysis is a widely recognized method that has been employed for decades by the U.S. federal government and many other entities [6], [28] to assess the social impact of new policies.

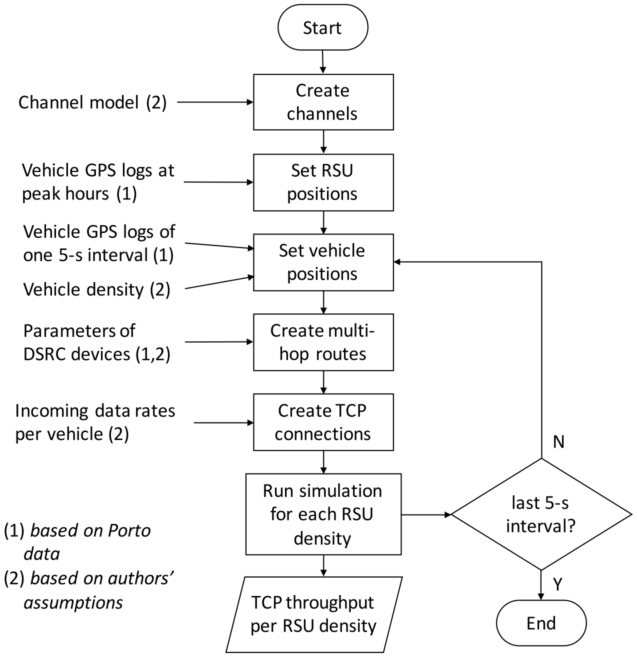


FIGURE 3. Simulation of throughput for one scenario of numerical assumptions. For each scenario, throughput is simulated several times, once for each RSU density and for each 5-second interval of vehicle positions.

A. NETWORK SIMULATION

The model represents packet streams that flow between each connected vehicle and one RSU which serves as a gateway to the Internet. Vehicles connect to RSUs either directly or through multiple hops with other vehicles acting as relays, as illustrated in Fig. 1. This is simulated at the transport, network, link and physical layers using the ns-3 network simulator [26]. The main steps of the simulation are represented in Fig. 3, and the simulation model is described below.

1) VEHICLE MOBILITY AND RSU LOCATIONS

A realistic model of vehicle positions is derived from the logs of vehicle GPS readings from Porto, which are collected every second for taxis, so every fifth reading marks the beginning of a time interval. GPS readings for buses are collected every 15 seconds, so we get positions interpolated every 5 seconds. The positions of vehicles other than buses are also derived from the GPS logs of taxis. Mobility is simulated as a series of "snapshot" positions in 5-second intervals, meaning that vehicles are simulated with static positions, representing a wireless network with non-moving nodes communicating for 5 seconds. After the simulation run completes and throughput rates are calculated for one time interval, the positions of the vehicles are changed to represent the network topology for the next 5 seconds, the communications simulation and throughput rate estimation is performed again, and so on.

The simulation accepts RSU density as input, and then places RSUs using the k-means clustering heuristic [29], with peak-hour vehicle positions as the input.

Vehicle and RSU antennas are placed in a tri-dimensional space. Vehicle X and Y coordinates are given by the GPS data. Z coordinates represent the height of antennas. All RSU antennas have a height of 7 meters, which is the average height of Porto RSUs as of March 2015. Bus antennas have a height of 3 meters (average of buses in Porto), and all other vehicles have height of 1.5 meters (as in [30]).

2) USE OF DSRC SPECTRUM FOR INTERNET ACCESS

75 MHz of spectrum allocated for DSRC is used in seven 10 MHz channels, of which one is reserved for control and management of all channels, and two other channels are reserved for safety applications [31]. We assume the four remaining channels are used for Internet access, as has been proposed in recent FCC proceedings [32]. In other words, Internet traffic is sent over channels that are not used for safety. Each OBU and RSU is equipped with four radios for non-safety traffic, i.e., one for each channel used for Internet traffic, which are independent from those used for safety.

It is assumed that each packet streams flow uses one channel. The channel to be used at each hop of the flow is chosen as the least used channel in the area simulated.

3) ESTIMATION OF THROUGHPUT

The throughput rate via DSRC for each vehicle is defined as the application-level data throughput achievable to or from each vehicle through a single or multihop path. We assume that the traffic sent to or from any given car equals the sum of the throughput over the DSRC network and the throughput over cellular to that car. These assumptions are accurate if the amount of traffic that is lost and the amount of traffic that is unnecessarily sent on both networks are negligible. This is reasonable as long as a cellular network is always available and has capacity to carry all traffic that cannot be carried over the vehicular network.

Steady-state throughput through DSRC is estimated for each 5-second interval. This simplifying assumption ignores the fact that vehicles move continuously during the interval. This form of analysis may miss some of the fluctuations in data rate as observed by a moving vehicle, but it allows for a good approximation of throughput when averaged over many time intervals as long as vehicles can switch off between the vehicular network and a ubiquitous cellular network as needed, so that data rate fluctuations have little effect on the total amount of traffic sent and received. This is a reasonable first-order estimate if the time to establish V2V and V2I hops is negligible, and this switching time with DSRC is expected to be roughly 300 milliseconds [31], [33]. To estimate steady-state throughput in a given time interval, the simulation is first run for an extended warm-up period before statistics are gathered.

Each DSRC-equipped vehicle is the endpoint of one and only one bidirectional flow with a RSU. However, any vehicle can also serve as a relay for data of a flow that has another vehicle as a destination, in case of multihop communications.

4) ENDPOINTS FOR TRAFFIC

Each RSU is a gateway to the Internet which a given vehicle connects to. We only model the traffic on the vehicular network, i.e., between vehicles and RSUs, so we treat the RSU as if it were the endpoint of a transport-layer connection rather than merely a gateway, as represented in Fig. 1 (b).

5) TRANSPORT LAYER

At each interval, a Transmission Control Protocol (TCP) connection is simulated between each vehicle and RSU it connects to. The TCP Maximum Segment Size (MSS) used is 2244 bytes, which is the maximum size of the packet that the 802.11 link layer supports without fragmentation (2304 bytes), minus 60 bytes for the link and IP headers [34]. That MSS is roughly similar to typical values for TCP connections traversing 802.11 networks.

6) NETWORK LAYER

IP packets are routed through the path with the minimum number of hops between the vehicle and a RSU, up to a maximum of three hops for each path. If a given vehicle can reach one or more RSUs through one-hop paths, then the path with the least path loss is selected. If the minimum number of hops in all paths is greater than one, then we select one path randomly among the paths with the minimum number of hops, such that each of those paths is equally likely.

7) LINK LAYER

The media access control (MAC) sublayer in the DSRC link layer is the one specified in the IEEE 802.11p amendment [35] of the IEEE 802.11 standards.

8) PHYSICAL LAYER

A hop is used between two nodes only if signal strength at the receiver exceeds 15 dB above the sensitivity threshold (-94 dBm). This is the criteria determined empirically in the bus network of Porto as the minimum quality for the pairs of nodes to transfer data. When the hop is used, packets are received at an error rate that depends on the signal-to-interference-plus-noise ratio (SINR), as described in [27] and [26].

The transmitted power is 14.6 dBm, obtained from measurements at the equipment output, which is also consistent with [36] and [37], and the gains of the transmission antennas are 16 dBi and 5 dBi for the RSUs and vehicles, respectively, which are consistent with the settings of the equipment in the Porto network.

The received signal is calculated according to the propagation loss model from [38] (urban microcell B1 variant).

This model is appropriate for urban areas, because vehicular networks are most useful in urban areas where density of vehicles is higher, as is demand for cellular networks. Moreover, it was preferred over other similar models because it is valid for the DSRC band (5.9 GHz), and it explicitly models two other characteristics that are relevant in vehicular networks: whether those nodes are in line-of-sight (LOS) or non-LOS (NLOS) [38], [39], and the antenna heights of vehicles and RSUs [3], [38].

Each interval each link is assumed to be in LOS or NLOS according with probability *Prob(LOS)* estimated as [40]

$$prob(LOS) = \begin{cases} \frac{d-300}{300} & for\ d < 300 \\ 0 & otherwise \end{cases}$$

[41] and [38] propose expressions which result in a similar LOS probability.

The difference between the median simulated loss and the median loss measured in Porto buses is less than 5 dB for most distances shorter than 200 meters, which shows the assumed model is a reasonable approximation for the observed loss. For example, at a distance of 100 m between a RSU and a bus, the median measured loss is 92 dB while the simulated loss is 95 dB. More than 95% of the hops observed in the Porto network are shorter than 200 meters.

B. BENEFIT-COST ANALYSIS

The second step of the methodology is to use DSRC throughput to estimate benefits and costs of Internet access at peak-hours. Our definitions are independent of who incurs those costs and who derives those benefits. This allows us to quantify the impact of deploying a new kind of infrastructure on total social welfare without making any assumptions about who pays for the RSUs, whether the operator of RSUs charges for the service, who pays for the service, or how much. Good answers to the questions can be found if and only if a new system would increase overall social welfare.

We define the benefit of Internet access through vehicular networks as the net present value of cost savings, which we derive under the following assumptions. All macrocellular carriers in the region being analyzed are assumed to be capacity-limited instead of coverage-limited. In a coverage-limited system, a carrier deploys the minimum number of towers to meet coverage requirements, and there will still be more capacity than needed even in the peak hour. Internet access through DSRC is not valuable in a region that has excess unused capacity. In contrast, in a capacity-limited system, a carrier deploys enough towers to meet capacity requirements, which means the system is expected to operate at full capacity during peak hours. Therefore, Internet usage in vehicles as a new source of mobile traffic should be met either via capacity expansion of the macrocellular networks, or via offload of part of the Internet traffic onto a DSRC network, as illustrated in Fig. 4. To serve more users or higher rate per user, a capacity-constrained carrier that is already using current technology throughout the spectrum available to it must deploy new towers.

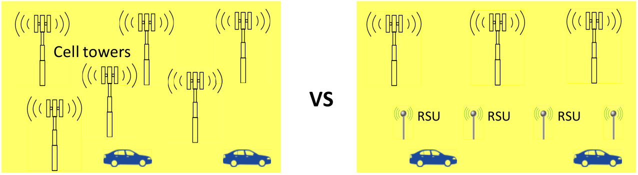


FIGURE 4. The economic benefit is the difference between the cost to provide Internet access for vehicles using only macrocellular towers, and the cost to carry part of the Internet traffic through the DSRC network.

Besides deployment of new towers, there are two other ways to increase macrocellular capacity. One is the acquisition of more spectrum, which increases capacity per tower. The other is changing the efficiency of the technology employed per tower, such as migrating from 3G to 4G equipment, or adding equipment to increase the number of sectors per tower. Since network designers will generally choose the approach for expanding capacity that is most cost-effective at the time, the marginal cost of increasing capacity is likely to be similar for all available approaches [42]. We assume for this analysis that the deployment of new towers is the preferred method.

It is assumed that devices send as much traffic as possible over the DSRC network in every interval. The amount of traffic carried through DSRC equals the reduction in the amount of traffic carried through cellular, meaning that devices switch between the DSRC and macrocellular network with negligible disruption, with no data being lost or transmitted in duplicity through both networks.

The net present value (NPV) of the benefit of Internet access per km^2 is $NPVB = \rho_{savedtowers} C_{tower}$ where C_{tower} is the average NPV per macrocell tower and $\rho_{savedtowers}$ is the total number of macrocell towers "saved" per km^2. It is given by

$$\rho_{savedtowers} = \frac{bpsOff\ FR}{s_{sector}\, bw N_{sectors}}$$

where *bpsOff* is the peak-hour, downstream DSRC throughput per km^2, $FR \geq 1$ is the frequency reuse factor, s_{sector} is the average downstream spectral efficiency in bps/Hz/sector, bw is the total bandwidth per macrocellular carrier used for downstream transmission, and N_{sector} is the number of sectors per macrocellular tower. We also assume that if there is sufficient capacity downstream then there is also sufficient capacity upstream, and that carriers are using Frequency Division Duplexing (FDD) so spectrum can be labeled as either upstream or downstream. This is reasonable because downstream traffic rates have been growing faster than upstream rates [43], and most tier-1 carriers currently use FDD [44].

The total cost of Internet access through DSRC per km^2 *NPVC* consists of three types of costs:

$$NPVC = NPVC_{RSU} + NPVC_{OBU} + NPVC_{Spectrum}$$

where $NPVC_{RSU}$, $NPVC_{OBU}$ and $NPVC_{Spectrum}$ are the NPV per km^2 of the costs of RSUs, OBUs and ITS spectrum, respectively, and are given as $NPVC_{RSU} = \rho_{RSU} C_{RSU}$, $NPVC_{OBU} = \rho_{OBU} C_{OBU}$,

$$\begin{aligned} NPVC_{RSU} &= \rho_{RSU} C_{RSU}, \\ NPVC_{OBU} &= \rho_{OBU} C_{OBU}, \\ NPVC_{Spectrum} &= \rho_{Spectrum} C_{Spectrum} \end{aligned}$$

where ρ_{RSU} is the number of RSUs for Internet access deployed per km^2, which is assumed to be independent and not shared with RSUs deployed for safety or purposes other than Internet access, ρ_{OBU} is the number of OBUs deployed per km^2, $\rho_{Spectrum}$ is the amount of ITS spectrum in MHz times the population density, and C_{RSU}, C_{OBU}, $C_{Spectrum}$ are the NPV per RSU, OBU, and MHz-pop, respectively.

In this analysis, we assume parameters that affect the NPV of cost and benefit are static, and will use numerical values that are reasonable for decision-makers that are looking several years into the future.

C. BASE CASE SCENARIO

The base case numerical values are listed below for the assumptions used in the estimates of the throughput of Internet access via DSRC, benefit and DSRC costs. Those assumptions apply for the results in Section V, unless otherwise stated.

1) MONETARY VALUES

The monetary values are in constant 2014 dollars. Benefit and cost NPVs are calculated at a real discount rate of 7% over a horizon of 10 years. The discount rate is consistent with the rate recommended by the U.S. Office of Management and Budget for benefit-cost analysis of federal programs [45]. Other analyses use similar rates [46], [47]. The 10-year horizon is long enough to evaluate the lifetime costs of the main elements of the model. For example, RSU lifetime was estimated to be 10 years in analysis for the U.S. Dept. of Transportation [48]. Although some costs such as macrocellular towers are incurred for a longer horizon, because of the 7% discount rate, their NPV is primarily determined in the first 10 years.

2) POPULATION DENSITY

We make the simplifying assumption that population density is constant throughout the region being analyzed. For the base case the population density is chosen as 5000 people/km^2, which is representative of Porto (5,600) [25] as well as large cities such as Boston or Chicago [49].

3) NUMBER OF VEHICLES ON THE ROAD AT PEAK HOURS PER CAPITA

Assumed as in Table 2, which is calculated as the product of vehicles owned per capita [49], fraction of time vehicle is in use and ratio of peak-hour usage to average usage [50]. We consider usage at peak hours because our calculation of benefit is based on data offload from capacity-limited cellular networks, and it is peak-hour usage that determines how much capacity a cellular carrier needs, and thus the cost that the carrier incurs.

TABLE 2. **Number of vehicles on the road at peak hours per capita, as a function of population density [24].**

People per km^2	Number of vehicles owned per capita	Number of vehicles on the road at peak hours per capita
10	1	0.077
200	0.8	0.061
1000	0.65	0.050
2000	0.6	0.046
3000	0.55	0.042
5000	0.44	0.034
12000	0.22	0.017

4) DSRC PENETRATION IN VEHICLES

Assumed as 25%. This is reasonable for a decision-maker looking 5 to 10 years ahead in the context of a mandate to deploy DSRC in all new cars [6], [47].

5) DATA TRAFFIC PER DSRC-EQUIPPED VEHICLE ON THE ROAD

At any 5-second interval during the peak hour, 50% of the DSRC-equipped vehicles on the road are endpoints for data being continually at 800 kbps (total downstream and upstream). The remaining vehicles are not endpoints for traffic, although they may relay packets for other vehicles in multihop connections. This is consistent with predictions that vehicular traffic will reach 5 GB/month in the coming years [51]. In reality, data rates vary from vehicle to vehicle at any given time, but since RSUs are typically in range of dozens of DSRC-equipped vehicles at all times during peak hour, this simplifying assumption should have limited effect on aggregate throughput.

6) SHARE OF DOWNSTREAM TRAFFIC

While a vehicle is transferring data, 90% of the data flows in the downstream direction (RSU to vehicle). In the Porto DSRC network, 92% of a session volume is downstream, on average, and [43] reports a similar ratio for the monthly usage per mobile device in the U.S.

7) UNIT COST OF MACROCELLULAR TOWER

The NPV of cost per macrocell tower over 10 years is \$750,000. Where carriers are leasing space on existing cell towers, this cost includes leasing fees. Where carriers build their own towers, a decade of leasing fees is replaced by CAPEX. A 10-year NPV of \$750,000 is roughly consistent with previous estimates [52]–[54], in 2014 dollars.

8) MACROCELLULAR SPECTRUM EFFICIENCY

The downstream average efficiency of a macrocell is 1.4 bps/Hz/sector, which is an accepted value for LTE-FDD rel. 8 [55]. Some devices will be more spectrally efficient, such as those using LTE-A, while usage of less efficient devices also continues (with efficiencies below 1 bps/Hz/sector [56]).

9) SECTORS PER MACROCELL

Each macrocell is divided in 3 sectors, which is consistent with [57] and others.

10) MACROCELLULAR BANDWIDTH

Any new tower deployed in a capacity-limited region is constrained by the bandwidth available for downlinks, and would operate over a downlink bandwidth of 70 MHz per sector. A tier-1 provider is estimated to hold roughly 30 MHz of downlink spectrum for LTE, on average [58], and spectrum in use for LTE is estimated at about half of total spectrum for mobile broadband. Substantial amounts of new spectrum are expected to be allocated [59], but its effective use may take several years for actual deployment.

11) MACROCELLULAR FREQUENCY REUSE FACTOR

The frequency reuse factor in macrocells is 1, which is consistent with a typical macrocellular network configuration with current technology [60].

12) UNIT COST OF DSRC RSU

The average NPV over 10 years of a DSRC RSU is $14,000. This is based on U.S. DOT estimates (average annual cost between $2,000-3,000 [48], including replacement costs every 5 to 10 years). However, in Section 4 we will consider variations of more than 50% from the base case value, as conditions about infrastructure availability may vary. For example, the city of Porto deployed RSUs for a Capex of between $1,200-4,000, by placing RSUs in existing structures (traffic poles, buildings, etc.) already owned by the city and already equipped with energy and backhaul access. The cost per RSU could be also be lower if RSUs deployed for Internet access are shared for safety or vice-versa, although sharing depends on many issues. These issues include whether the optimal placement of RSUs for Internet access matches the placement for safety communications and whether devices for Internet access and devices that are safety-critical are placed under shared control. For the base case value of the cost per RSU, no sharing is assumed. On the other hand, costs can be significantly higher if new poles, energy and communications infrastructure must be built entirely.

13) UNIT COST OF DSRC OBU

The NPV of the cost of a DSRC OBU is $350. This is based on U.S. NHTSA estimates [47] considering four radio interfaces and antennas per vehicle.

14) UNIT COST OF DSRC SPECTRUM

The cost of DSRC spectrum is $0.10 per MHz per population (MHz-pop). This value is uncertain, as the cost of spectrum depends on frequency [42], [61]–[63], and the market value above 5 GHz is not well-established.

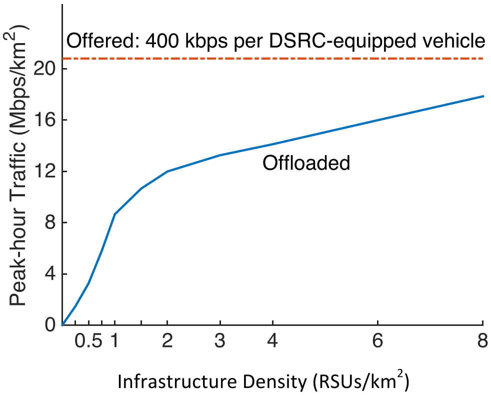


FIGURE 5. Average traffic offered and offload rate at a peak hour, for the base case scenario.

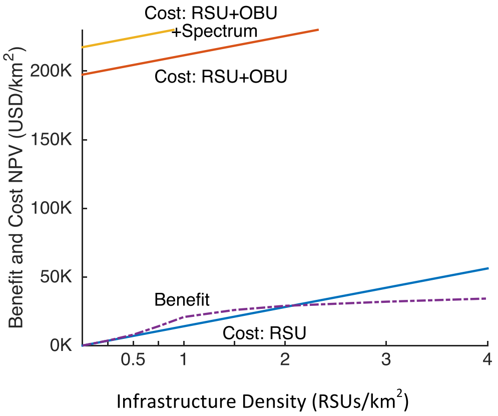


FIGURE 6. Benefit and cost for varying infrastructure density, for the base case scenario.

V. RESULTS

This Section presents the simulated DSRC throughput, benefit and cost results for the base case scenario, and how those results vary if base case values change.

A. BASE CASE SCENARIO

Fig. 5 shows throughput as a function of RSUs per km^2 under base case assumptions. Throughput increases with more infrastructure, as the number of vehicles that reach a RSU increases. However, the marginal gains in offload rate decrease as the RSU density exceeds 2 per km^2. This matters because while increasing RSU density increases DSRC throughput and therefore benefit, it also increases cost. This can be seen in Fig. 6, which shows both benefits and costs as a function of RSU density under the same assumptions. Fig. 6 shows that for the base case values, the maximum difference between benefits and costs occurs at 1 RSU/km^2, for which benefits exceed the cost of RSUs by 50%. If spectrum has already been allocated and OBUs purchased, as is likely to occur for safety applications, then those are sunk costs. Consequently, the benefits of deploying RSUs exceed the costs, and doing so will increase social welfare. However, Fig. 6 also shows that the benefit of Internet access is considerably less than the cost of OBUs. Thus, the value

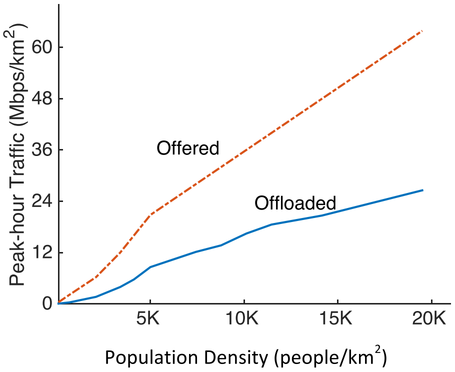


FIGURE 7. **Average traffic offered and offload rate at a peak hour for varying population densities and other parameters fixed at base case values, optimal RSU quantity at each point (i.e. at RSU quantity that maximizes the NPV of benefit minus the NPV of cost for each population density: 1 to 2 RSUs/km^2).**

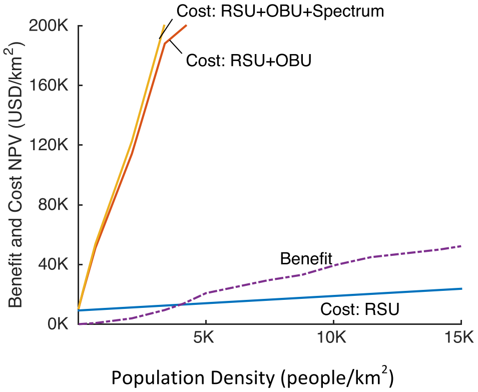


FIGURE 8. **Benefit and cost for varying population densities (and other parameters at base case values), and optimal RSU quantity at each point.**

of deployment of vehicular networks for Internet access alone, i.e., without consideration of the improvements in highway safety, are not sufficient to justify the deployment of OBUs and the allocation of spectrum in the base case scenario.

Statistical significance is sufficient to support conclusions. We average throughput over 10 time intervals for 1000 vehicles in a 20 km^2 region. If we make the simplifying assumption that the throughputs of these 1000 vehicles are mutually independent, although throughputs at different time intervals are not, then mean throughput is 170 kbps (which is about 40% of offered load), and the confidence interval is within 7% of the mean.

B. IMPACT OF POPULATION DENSITY

Subsection V.A showed that deploying RSUs can increase social welfare in the baseline case, which corresponds to a densely populated city such as Porto or Chicago [64]. However, that may not be the case everywhere. In a more densely-populated area, there will be a greater density of vehicles and more on the road at peak hours. Therefore, more in-vehicle OBUs will be used, and more RSUs will be deployed for those vehicles to connect to, so OBU and RSUs costs increase with population density. On the other hand, throughput per unit of area, and hence the benefit, are also expected to increase.

Fig. 7 and Fig. 8 show throughput, benefits, and costs as a function of population density. Traffic per vehicle, penetration, unit costs and spectrum parameters are held constant at base case values. The benefit and cost of RSUs in Fig. 7 depend on the quantity of RSUs for each population density, which is chosen as follows. For the values of population density in which the NPV of benefit of Internet access exceeds the NPV of cost of RSUs, the number of RSUs chosen is the quantity that maximizes the difference between the NPV of benefit and the NPV of RSU cost. For the population density values in which the NPV of benefit is lower than the NPV of RSU cost for any quantity of RSUs, we calculate the quantity of RSUs as a linear extrapolation from the population density range which the NPV of benefit is greater than the NPV of RSU cost.

Fig. 7 shows that offered traffic increases rapidly as a function of population density, which is expected because quantity of vehicles increases with population density. DSRC throughput also increases with population density, although at a slower pace than offered traffic because competition for the use of the wireless medium limits offload.

Fig. 8 shows that benefit increases faster than RSU cost. The reason is that throughput grows roughly proportionally to population but the optimal number of RSUs rises at a slower pace. For base case assumptions, the threshold for which benefit exceeds cost is 4000 people/km^2. If decisions about whether to deploy RSUs are made on a city-wide basis, this means cities with population densities at least as great as Chicago or Porto would benefit from RSU deployment, assuming there is already spectrum allocated and a mandate of DSRC OBUs for safety purposes. However, RSUs could be deployed within an area much smaller than a city, and many cities with more modest population densities have some neighborhoods with densities over 4000 people per km^2.

Fig. 8 shows that benefit grows faster than RSU cost, but OBU cost grows much faster than benefit. Under a mandate, every vehicle will (eventually) incur OBU costs, but only the vehicles on the road at peak hours add to the benefits. However, if adoption is voluntary, then owners of vehicles that are often in use are more likely to adopt, and this would also have the effect of increasing the ratio of DSRC-equipped vehicles on the road at peak hour to total cars. Thus, if many of the DSRC equipped cars are driven extensively, then this will also increase the net benefit of deploying RSUs.

C. IMPACT OF OBU PENETRATION AND RATES OF INTERNET DATA

OBU penetration in vehicles may increase rapidly over time and is likely to affect benefit and costs. With higher penetration, offered load per km^2, throughput, and ultimately benefit increase. Moreover, the optimal number of RSUs to carry that throughput increases with penetration as well. Fig. 9 shows benefit and costs as a function of penetration,

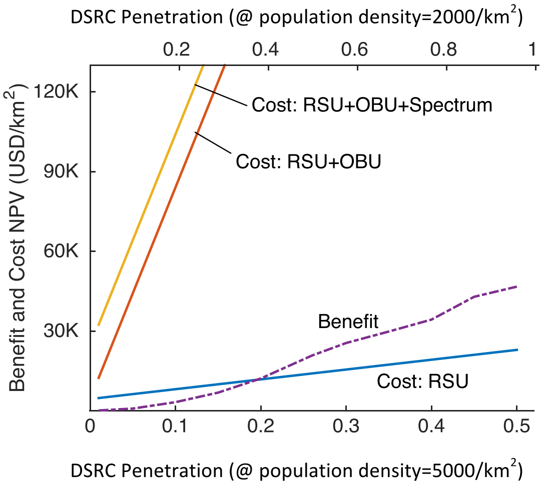


FIGURE 9. Benefit and cost for varying values of DSRC penetration (and other parameters at base case values), and optimal RSU quantity at each point. Each horizontal axis refers to a different population density.

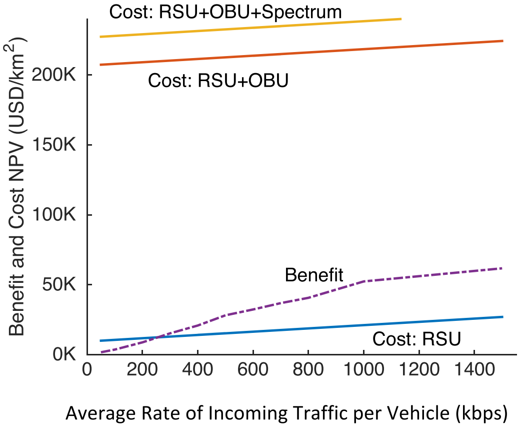


FIGURE 10. Benefit and cost for varying rates of incoming traffic per DSRC-equipped vehicle on the road (and other parameters at base case values), and optimal RSU quantity at each point.

with all parameters, except penetration, at base case values and the RSUs densities chosen as described in subsection V.B. The top horizontal axis shows penetration for a lower population density (2000 people/km^2), while the bottom horizontal axis shows penetration for the base case population density (5000). Fig. 9 shows that as OBU penetration increases, benefit increases faster than RSU cost. Thus, in cities where RSU deployment does not result in benefit exceeding RSU cost within the current planning horizon, this may change after a few years as penetration increases. For the base case assumptions, the benefit of Internet access exceeds RSU costs when penetration is 0.19 or greater in a city with population density of 5000/km^2. (For a population density of 2000 people/km^2, benefit exceeds cost when penetration is 0.37 or greater).

However, OBU cost increases much faster than benefit, thus if penetration increases over time, the difference between OBU cost and benefit is also likely to increase. In this situation, if there were no benefits other than Internet access, then social welfare would decrease. But that could only be true if DSRC had no safety benefits whatsoever, which is unlikely.

Similar results are obtained for varying data rate per vehicle, which is expected to increase rapidly over time [56], [65]. Fig. 10 shows the benefits and costs as a function of incoming traffic per vehicle, assuming the population density, quantity of vehicles, penetration, unit costs, and spectrum parameters are held constant at the base case values for all values of traffic considered, and the RSUs densities are chosen as described in subsection V.B.

The difference between the benefit of Internet access and RSU cost increases with traffic per vehicle, similarly as with OBU penetration. If traffic or penetration increase over time as predicted, then benefit will eventually exceed RSU cost in less populated areas where this is not the case soon after the mandate is effective. In subsection V.B it is shown that benefit exceeds RSU cost for locations with population density above 4000 people per km^2, with the base case assumption of traffic per vehicle. Since Fig. 10 shows that the difference between the benefit of Internet access and RSU cost increases with traffic per vehicle, and if traffic will increase over time as some predict, then benefit would exceed RSU cost in locations with population densities below 4000 people per km^2 over time.

Fig. 10 also shows that, under the base case scenario for the other assumptions, the benefit of Internet access exceeds RSU cost for traffic per vehicle above 250 kbps at peak hours. This corresponds to a monthly usage of 3 GB per vehicle. Thus, deploying RSUs would still result in the benefit exceeding RSU cost soon after the mandate becomes effective in the densely-populated urban area represented by our base case if data rate is about half of what some are currently predicting.

The average data rate of a DSRC-equipped vehicle may also exceed the average data rate of all vehicles if vehicle owners purchase OBUs voluntarily, rather than only in response to a mandate. The owners who adopt voluntarily would be the ones who benefit the most. If owners are charged for Internet service based on usage, then more owners of vehicles with higher volumes of Internet traffic would opt in, and average data rates could be much greater than the base case. For example, a bus company offering Internet service for passengers (such as the one in Porto) might voluntarily install OBUs as soon as RSUs are operating because the bus company expects a data rate per vehicle that is well above average, and carrying that traffic over a cellular network would be expensive. Thus, for a given OBU penetration rate, the benefit of Internet access will exceed costs at a lower population density if there is a significant level of voluntary adoption of OBUs.

1) BENEFIT UNDER HIGH OBU PENETRATION OR DATA RATES

We also examined the impact on cost-effectiveness of high data rates and OBU penetration. Since benefit is proportional to throughput, we investigated whether the latter

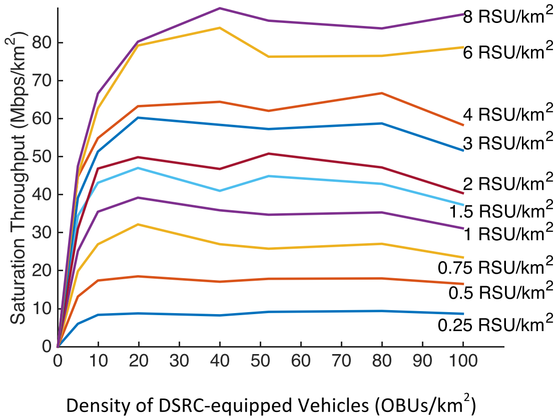


FIGURE 11. Saturation throughput of the vehicular network for varying density of OBU-equipped vehicles and data rates of 100 Mbps/OBU. Each line refers to a fixed RSU density.

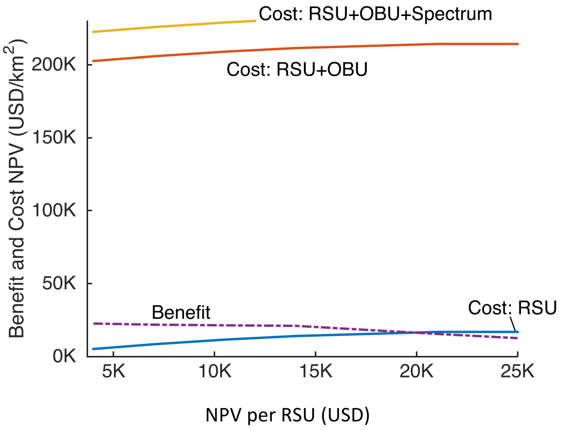


FIGURE 12. Benefit and cost for varying PV per RSU (and other parameters at base case values), and optimal RSU quantity at each point.

increases or collapses for high network load. As data rate of incoming traffic increases, throughput increases rapidly until it reaches a peak, and then remains within a small percentage of its peak for higher loads, regardless of RSU density. This limit at arbitrarily high load is called saturation throughput [66], [67], and Fig. 11 shows the relationship between saturation throughput per km^2 and density of OBU-equipped vehicles. Data rates of incoming traffic at each path are high enough to keep the TCP transmission buffers constantly full, and curves for several RSU densities are shown. The graph shows that saturation throughput increases linearly when vehicle density is low, and then remains close to its maximum for all OBU densities above some threshold, regardless of RSU density. The fact that throughput is close to peak even for much higher loads than the base case value means that congestion and interference never cause a serious loss of throughput (and therefore benefit), probably thanks to mechanisms such as MAC-level collision avoidance and transport-layer congestion control. This is important, because the number of DSRC-equipped vehicles will increase over time if the U.S. Dept. of Transportation mandates the technology for all new cars, and data rates of incoming traffic are also expected to increase sharply over time [43], [65]. As a result, cities with vehicular networks need not fear that benefit will decline as load goes up every year.

D. COST PER RSU, COST PER OBU, AND MACROCELLULAR COSTS

We also examined the effect of the unit costs of OBUs, RSUs and macrocellular towers on the cost-effectiveness of DSRC.

Fig. 12 shows the benefits and costs as a function of RSU unit cost. The base case values of population density, the quantity of vehicles, penetration, traffic, OBU and macrocellular unit costs, and spectrum parameters are assumed. The RSU density for each value of RSU unit cost is chosen to maximize the difference between benefit and RSU cost per km^2, as in the previous sections. The cost per RSU affects that optimal quantity of RSUs, which influences DSRC throughput. We found that the total benefit and cost results are robust to a wide variation of costs per RSU. Even if this cost is 30% higher (or lower) than the base case, benefit of Internet access will still exceed total RSU cost.

However, that result might change if the cost per RSU is radically different than the base case. For example, if RSUs are deployed in places that require expensive poles or lack of access to commercial power or communications, then the cost per RSU might be much higher than in the base case, which may prevent RSU deployment and result in no benefit at all. On the other hand, if the decision to deploy RSUs are made by a municipality that already has pole, energy, and backhaul infrastructure available, cost per RSU may be low, and two implications are possible. First, it may be worthwhile to deploy more RSUs to increase total throughput, compared to locations with more expensive infrastructure. Second, in locations with cheap infrastructure, RSU deployment might be beneficial even for less densely populated cities than the ‘‘threshold’’ density shown in Section V.B for base case assumptions, as long as spectrum and OBU costs are sunk under a mandate.

We also examined the effect of the cost per OBU on total benefit and costs. If a mandate was to be justified by Internet access only, then the benefit of Internet access alone should exceed all DSRC costs. However, in the previous sections it is shown that the cost of OBUs far exceeds benefit. We have varied the assumed cost per OBU and found the sum of RSU and OBU costs would still exceed the benefit of Internet access even if the cost per OBU falls by more than 80%.

It is possible for the cost per OBU to decrease that much if, and probably only if, DSRC is mass-produced at a scale comparable to Wi-Fi. Such a cost decrease might be possible considering that at the physical level, DSRC is mostly an adaptation of the Wi-Fi 802.11a standard for the 5.9 GHz band. Currently, Wi-Fi radios with antennas cost no more than a few tens of dollars.

If the NPV of the cost per macrocellular tower is higher than the base case assumption, then the benefit of Internet access exceeds RSU cost in less populated areas than in the base case scenario. On the other hand, if macrocellular cost is lower than in the base case, than the benefit might be lower. However, we find that the results in previous Sections do not change substantially if the cost per macrocellular tower changes over a range of 20% below or above the base case value.

Likewise, we find that the benefit of Internet access exceeds RSU cost if as much as 20% more bandwidth per carrier is in use. Spectrum holdings for cellular service may increase over time if the growing demand for mobile Internet triggers decisions to reallocate spectrum from other uses to cellular – for example, in 2010 the U.S. National Broadband Plan recommended increasing the amount of spectrum available for broadband by 500 MHz. However, spectrum reallocations are not frequent and take years to become effective – 65 MHz were auctioned in 2015, being the first significant addition to mobile spectrum since 2008 in the U.S. [56]. Therefore, over a given period, the amount of spectrum may increase less than the rapid growth expected for traffic per vehicle (which increases benefit), which suggests that the growth in cellular spectrum is not likely to change our estimates that the benefit of Internet access exceeds RSU cost for base case values of the other assumptions.

VI. CONCLUSIONS

In this paper, we analyze benefits and costs of Internet access through DSRC. We find that if there has already been a mandate to deploy DSRC in new vehicles, then the deployment of RSUs for Internet access increases social welfare. This is true for dense urban areas, when OBU penetration is representative of a few years after a mandate becomes effective, peak-hour Internet traffic per vehicle is compatible with forecasts for the next years, and even when those RSUs are not shared with safety or other applications. Moreover, RSU deployment is likely to become welfare enhancing in the future for many less-populated areas as well, as long as penetration or Internet traffic increases over time.

Under a mandate to deploy OBUs, our results show that the OBU cost alone exceeds benefit. However, it has been estimated that an OBU mandate will accrue significant road safety benefits [6], [47], which has motivated the allocation of DSRC spectrum and the possibility of a mandate to deploy DSRC in all new vehicles in the U.S. If this mandate occurs, then the decision of whether to use DSRC networks for Internet access becomes a decision about whether to deploy roadside infrastructure that can serve as a gateway to the Internet. For this decision, both OBU and spectrum costs would be sunk, and if the benefit of Internet access exceeds RSU cost, then a decision to deploy RSU infrastructure would increase social welfare. Our results show that benefit does exceed RSU cost under base case assumptions, which correspond to dense urban areas.

Benefits and costs are both affected by population density. If all else is equal, the benefit of Internet access through DSRC minus the cost of RSUs is greater when population density is greater. With base case assumptions, benefit exceeds RSU cost in locations with population density above 4000 people per km^2, i.e. only in fairly densely populated urban areas. However, this should change over time. Under an OBU mandate, the volume of traffic per vehicle and OBU penetration are both likely to rise rapidly beyond our baseline assumptions in the coming years. With this growth, our results show that the benefit of Internet access minus RSU costs also increases. Thus, if all assumptions are close to base case values except OBU penetration and traffic per vehicle, then the benefit will exceed the cost of RSUs in regions with lower and lower population densities over time. Therefore, the deployment of RSUs will become social-welfare-enhancing over more of the country. However, there will remain areas where deployment of RSUs does not enhance social welfare, including those rural areas where population density is so low that cellular networks are not capacity-limited, i.e., they have excess capacity and don't need offload.

Since benefit is proportional to throughput, we also examined how it scales for high levels of load in the vehicular network, which is likely to happen in the future. We find that even for arbitrarily high loads, throughput per unit of area (and thus benefit) approaches a saturation level that remains close to the maximum achievable throughput, meaning that the cost-effectiveness of vehicular networks will not decline even as Internet traffic and the penetration of OBUs in vehicles grow sharply as predicted.

RSU cost also affects whether deployment of RSUs would increase social welfare, and RSU cost varies from community to community. For example, all else being equal, benefits of Internet access through DSRC minus RSU costs will be lower where the provider has to acquire infrastructure (poles, backhaul, etc.), than where RSUs are deployed by a municipality that already has infrastructure available, or where part of the RSU cost is incurred for another purpose, e.g. a given RSU is shared for safety and Internet traffic.

Like any model of a complex system, our analysis is based on a number of simplifying assumptions, some of which we may explore further in future research, such as the variability in traffic per vehicle and among vehicle types, and the dynamics of traffic, penetration, and costs over time. However, the conclusion that the benefit exceeds RSU cost in urban areas but is lower than the sum of RSU, spectrum, and OBU costs is sufficiently robust, such that a small change of around 20% in any of these assumptions would not change it. If reality differs from the base case even more than this, this is most likely either because of our assumption about a mandate or our assumption about mobile traffic levels. For example, if data rates are substantially higher (or lower) than our baselines estimate of 5 GB per month per vehicle, then the population density required for the benefit of Internet access through DSRC to exceed the cost of RSUs may be less (or more) than our estimated 4000 people per km^2, respectively.

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