Scheduling in Green Vehicular Infrastructure with Multiple Roadside Units

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***Abstract*—Smart scheduling can be used to reduce infrastructure energy costs in vehicular roadside networks [1]. In this paper we consider the scheduling problem when there are multiple roadside units (RSUs) in tandem. In this case it is often desirable to load balance the energy consumption across the roadside units so that energy provisioning costs can be reduced as much as possible. We first derive an integer linear programming bound on the min-max energy usage of the roadside units for a given input sample function. This bound is used for comparisons with two proposed on-line scheduling algorithms. The first is a low complexity First-Come-First-Assigned (FCFA) scheduler which makes greedy RSU selections followed by a minimum energy time slot assignment. The second algorithm, the Greedy Flow Graph Algorithm (GFGA), makes the same RSU selection but reassigns time slots whenever a new vehicle is assigned to the same RSU. This is done using a locally optimum integer linear program that can be efficiently solved using a minimum cost flow graph. Results from a variety of experiments show that the proposed scheduling algorithms perform well when compared to the energy lower bounds. Our results also show that near-optimal results are possible but come with increased computation times compared to our heuristic algorithms.**

I. INTRODUCTION

In certain vehicular installations, the location of vehicles passing through roadside unit radio coverage can be predicted with a high degree of accuracy. This information can then be used to reduce downlink infrastructure-to-vehicle energy communication costs [1] by scheduling traffic when vehicles are in favourable energy locations. An example of this is illustrated in Figure 1. In this example, vehicle v is shown at two different times, t_1 and t_2, and at corresponding distances from the RSU given by d_1 and d_2, respectively. Communication at time t_2 may be preferred by the RSU, if the energy costs are lower compared with those at time t_1.

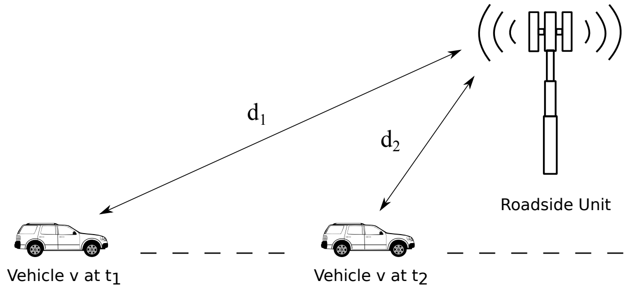

Fig. 1. Roadside Unit (RSU) Example. Vehicle v is shown at two different times, t_1 and t_2, and distances from the RSU, where $d_1 \gg d_2$. Communication at time t_2 is preferred in terms of RSU energy cost.

In this paper we consider the scheduling problem when there are more than one roadside units (RSUs) in tandem. When this is the case it may be desirable to energy balance the load across the roadside units so that energy provisioning costs are minimized as much as possible. An integer linear programming bound for the min-max energy usage of the roadside units is derived for a given input sample function. This bound is used for comparisons with two proposed on-line scheduling algorithms. The first is a low complexity First-Come-First-Assigned (FCFA) scheduler which makes greedy RSU selections followed by a minimum energy time slot assignment. The second algorithm, the Greedy Flow Graph Algorithm (GFGA), makes the same RSU selection but reassigns time slots whenever a new vehicle is assigned to the same RSU. This is done using a locally optimum integer linear program that can be efficiently solved using a minimum cost flow graph. Results from a variety of experiments show that the proposed scheduling algorithms perform well when compared to the energy lower bounds. Our results also show that near-optimal results are possible but come with increased computation times compared to our heuristic algorithms.

A. *Related Work*

Recent research in vehicular networks has included topics such as routing algorithms [2], applications [3], security [4], and medium access control performance of the IEEE 802.11p standard [5]. For example, studies have illustrated the suitability of IEEE 802.11p for highway applications [6] [7]. In [8][9] [10], proxy vehicles are used to decrease vehicle contention and improve roadside unit utilization.

Vehicle transmitter power control has been used as a mechanism for trading off network connectivity and reduced inter-vehicle interference [5] [11] [12]. However, the energy efficiency for vehicular ad hoc networks has typically not been addressed, as vehicles are usually assumed to have unlimited energy reserves. In addition, from the roadside infrastructure point of view, most work assumes that wired power is available at reasonable cost, which may not always be the case.

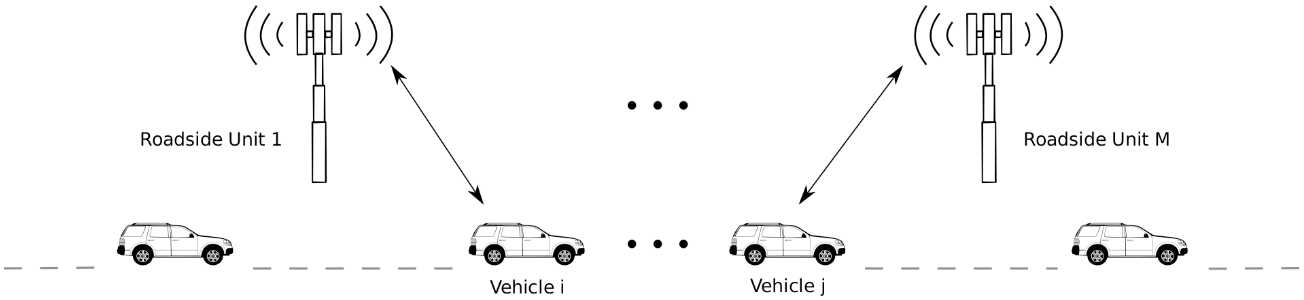

Fig. 2. Multiple Roadside Units (RSUs). Vehicles pass through the coverage areas of M roadside units, any of which can provide the required vehicular communications.

Traffic scheduling at the roadside unit has been considered in [13] where simple schedulers were based on transmission requirements and packet deadlines, but without considering the energy consumption of the infrastructure. In [14], an optimization is used to maximize the total throughput of an RSU given the locations and velocities of vehicles within the RSU coverage range. A scheduler was considered which was designed for use in the IEEE 802.11e contention free periods. As in the other studies referenced above, the energy consumption of the RSU was not taken into consideration, and this is the focus of our paper.

II. SYSTEM MODEL AND MIN-MAX ENERGY BOUND

A roadside scenario is considered which consists of a tandem set of M roadside units (RSUs). This type of arrangement will be common in cases where high capacity is needed to accommodate peak traffic periods. An example of this is given in Figure 2 where vehicles are shown traveling in the same direction, but bidirectional traffic is allowed. In the figure, RSU 1 and RSU M are shown communicating with vehicles i and j, respectively. In our development we will assume that all vehicles pass by the same set of RSUs, but this is not a requirement. It is assumed that when a vehicle v enters the coverage area of RSU 1, it communicates its speed, direction and communication requirements, given by R_v bits, to the system. We assume that each RSU has a single radio and can communicate with only one vehicle at a given time, but the RSUs can operate independently without interference. Channel time is assumed to be time-slotted and power control is used on the downlink (i.e., RSU-to-vehicle direction) so that each time slot can carry B bits, regardless of vehicle location within a given RSU coverage area. This can be accomplished in different ways such as using a short two-way handshake prior to downlink user data transmission.

The objective is to schedule incoming vehicular requests so that downlink (DL) energy use is load-balanced across the multiple RSUs. Due to the coverage range associated with RSUs, the average power consumption of an energy efficient RSU design may be strongly dominated by downlink transmission power. Note that since the vehicular radios operate from the vehicle engine, they are assumed to have unlimited energy reserves. For this reason, the RSU prefers to communicate with nearby vehicles rather than more distant ones. In the example shown in Figure 1, communications at time t_2 is preferable to time t_1 since $d_1 \gg d_2$. To use this option however, requires that there is sufficient packet delay tolerance, and in this paper we assume that any vehicle can be served from any of the M RSUs. The scheduling must also be done in a way which guarantees the packet reception requirements of the vehicles are fulfilled.

Given an input sample function of arriving vehicles with known speed and traffic requests, a lower bound on the optimum min-max scheduling is derived. In the input sample function we assume that there are N vehicles indexed by the set $\mathcal{N} = \{1, 2, \ldots, N\}$, M RSUs indexed by the set $\mathcal{M} = \{1, 2, \ldots, M\}$ and that there are T time slots given by the set $\mathcal{T} = \{1, 2, \ldots, T\}$ over which the scheduling is to occur. R_v is the communication requirement for vehicle v in bits, which requires $H_v \triangleq \lceil R_v/B \rceil$ time slots. We define the following set of binary scheduling variables.

$$K_{i,j,t} = \begin{cases} 1 & \text{if RSU } i \text{ sends to vehicle } j \text{ in} \\ & \text{time slot } t, \\ 0 & \text{otherwise.} \end{cases} \qquad (1)$$

The energy cost for downlink communications from RSU i to vehicle j during time slot t is defined by $\epsilon_{i,j,t}$. A lower bound on total energy use can then be computed using the following integer linear program (ILP).

$$\underset{K_{i,j,t}}{\text{minimize}} \quad \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{M}} \sum_{j \in \mathcal{N}} \epsilon_{i,j,t} \, K_{i,j,t} \qquad (2)$$

$$\text{subject to} \quad \sum_{i \in \mathcal{M}} \sum_{t \in \mathcal{T}} K_{i,j,t} = H_j, \quad \forall j \in \mathcal{N} \qquad (3)$$

$$\sum_{j \in \mathcal{N}} \sum_{t \in \mathcal{T}} \epsilon_{i,j,t} \, K_{i,j,t} \le \mathcal{E}, \quad \forall i \in \mathcal{M} \qquad (4)$$

$$\sum_{j \in \mathcal{N}} K_{i,j,t} \le 1, \quad \forall i \in \mathcal{M}, \forall t \in \mathcal{T} \qquad (5)$$

$$K_{i,j,t} \in \{0, 1\}, \quad \forall \{i \in \mathcal{M}, j \in \mathcal{N}, t \in \mathcal{T}\} \qquad (6)$$

In ILP 2 to 6, the objective function is simply the total DL energy used by the RSUs. Constraint 3 ensures that vehicle communication requirements are fulfilled by summing the appropriate values of $K_{i,j,t}$ over all RSUs, i.e., vehicle j can be served its full requirement by multiple RSUs. Constraint 4 places a common upper bound, $\mathcal{E}$, on the total energy used by each RSU. Since $\mathcal{E}$ is not known a priori, we can do a binary search on its value, solving ILP 2 to 6 each time, to get the minimum value of $\mathcal{E}$ that achieves an optimal min-max energy bound, i.e., a bound on the best load balancing possible. Constraint 5 ensures that a given time slot can only contain a single transmission, but allows for simultaneous operation of the M RSUs.

ILP 2 to 6 can be solved directly using branch and bound techniques, and CPLEX 8.1.0 has been used with data generated from MATLAB. These results are used for comparisons with on-line algorithms to be introduced in the next section.

III. ONLINE SCHEDULING ALGORITHMS

The results in Section II give a lower bound on the downlink min-max RSU energy needed to fulfill vehicular packet requirements. In order to compute these bounds, the energy costs associated with a given packet transmission, $\epsilon_{i,j,t}$, must be known. Although it is difficult to precisely know this information in general situations, in certain scenarios excellent estimates of this cost can be readily made [15][16]. Accordingly, we consider a highway scenario where vehicles may travel at different speeds, but maintain their own speed throughout the RSU coverage areas [17]. When vehicles enter the RSU coverage area, they announce their location, direction and speed, information that can subsequently be used to estimate future energy transmission costs assuming distance dependent exponential path loss propagation [15][16].

In the following sections we present two algorithms that operate to load balance the energy use across the RSUs, with varying levels of complexity and performance.

A. *First-Come-First-Assigned (FCFA) Scheduler*

The First-Come-First-Assigned (FCFA) scheduler uses both a greedy RSU selection and a greedy assignment of time slots. The details are shown in Algorithm 1. When a vehicle enters the network of RSUs, the RSU with the least accumulated energy usage is selected. This is shown in Step 5 and this vehicle is added to the set of vehicles assigned to that RSU, i.e., $\mathcal{S}_r$. Time slots (H_v for vehicle v) are then assigned from those available (i.e., from the set $U_{r,t}$) which minimize the cost of serving that vehicle. This is shown in Step 6. Once these time slots have been allocated, in Step 7 they are removed from $U_{r,t}$ and are unavailable to any subsequently arriving vehicles. The value of $\mathcal{C}_{i,t}$ is also updated. In the version of FCFA used for the results in this paper, rather than assigning the vehicle to a particular RSU, we view the H_v time slot requirement for vehicle v to be H_v separate one time slot vehicles, allowing them to be assigned across multiples RSUs.

B. *Greedy Flow Graph Algorithm (GFGA)*

As in the FCFA algorithm, in the Greedy Flow Graph Algorithm (GFGA), RSU selection is made for a newly arrived vehicle based on minimum RSU energy use. Once the target RSU is chosen, time slots are allocated to the vehicles which are assigned to that RSU based on a minimum cost energy schedule. This is computed using all currently available vehicular information and remaining backlog, and is recomputed whenever a new vehicle arrival occurs. The algorithm is shown in Algorithm 2 and is described in detail as follows.

Algorithm 1 First-Come-First-Assigned (FCFA) Scheduler

```
1:  $U_{r,t}$ = set of unassigned RSU $r$ time slots at time $t$.
2:  $\mathcal{C}_{r,t}$ = accumulated energy usage of RSU $r$ at time $t$.
3:  for all $t \in \{0, 1, \ldots\}$ do
4:      for each vehicle $v$ that arrives to the system (at time $t$) do
5:          Assign $v$ to RSU $r = \arg\min_{i \in \mathcal{M}} \mathcal{C}_{i,t}$.
            (i.e., $\mathcal{S}_r \leftarrow \mathcal{S}_r \cup v$.)
6:          Assign time slots to $v$ from the set $U_{r,t}$ that minimizes the energy cost of communication with vehicle $v$.
7:          Update $U_{r,t}$ by removing those time slots assigned in Step 6 and update the value of $\mathcal{C}_{i,t}$ to account for the new assignments.
8:          Update the schedule for RSU $r$ using the solution generated in Step 6.
9:      end for
10:     Using the current schedule for each RSU, continue RSU-to-vehicle transmission (at time slot $t$).
11: end for
```

When a new vehicle arrives to the system, it is assigned to the RSU which currently has the minimum accumulated energy usage. $C_{i,t}$ is defined to be the energy usage for RSU i at time t as shown in Step 6. $\mathcal{S}_r \subseteq \mathcal{N}$ is defined to be the set of active vehicles currently assigned to RSU r. In Step 7 we update the set of time slots for which all vehicles assigned to RSU r will be active. Then in Step 8 we use these updated inputs to find the minimum energy time slot assignment by solving the following ILP.

$$\underset{K_{r,j,t}}{\text{minimize}} \quad \sum_{t \in \mathcal{T}_r} \sum_{j \in \mathcal{S}_r} \epsilon_{i,j,t} \, K_{r,j,t} \tag{7}$$

$$\text{subject to} \quad \sum_{t \in \mathcal{T}_r} K_{r,j,t} = \widetilde{H_j}, \quad \forall j \in \mathcal{S}_r \tag{8}$$

$$\sum_{j \in \mathcal{S}_r} K_{r,j,t} \leq 1, \quad \forall t \in \mathcal{T}_r \tag{9}$$

$$K_{r,j,t} \in \{0,1\}, \quad \forall \{j \in \mathcal{S}_r, t \in \mathcal{T}_r\} \tag{10}$$

ILP 7 to 10 is similar to ILP 2 to 6 except that it solves the minimum energy schedule for a single RSU r, using the currently available inputs $\mathcal{S}_r$ and $\mathcal{T}_r$. The objective function therefore only considers the energy cost for RSU r. Constraint 8 satisfies the *residual* (i.e., remaining unserved) transmission requirement for vehicle j, denoted by $\widetilde{H_j}$. The other constraints follow similarly from ILP 2 to 6. In Step 8, once the new assignments are made, the value of $\mathcal{C}_{i,t}$ is updated. As in the FCFA scheduler, rather than assigning the vehicle to a particular RSU, we view the H_j time slot requirement of vehicle j to be H_j separate one time slot vehicles, allowing them to be assigned across multiples RSUs.

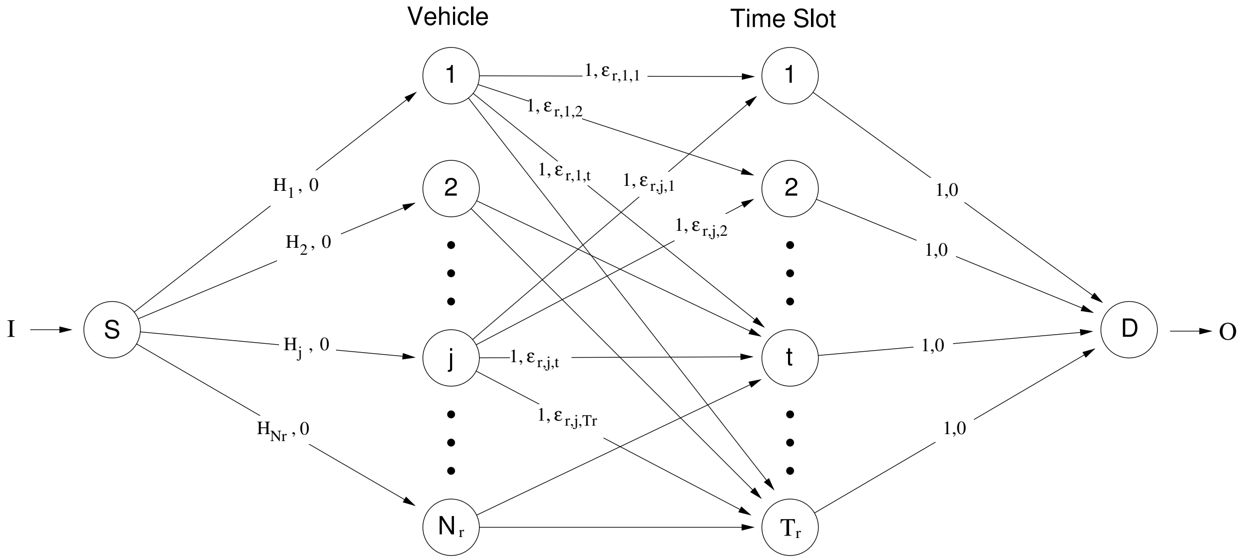

Fig. 3. Minimum Energy Flow Graph Scheduler. Each edge is labeled with an ordered pair, $(u_{r,j,t}, \epsilon_{r,j,t})$, where $u_{r,j,t}$ and $\epsilon_{r,j,t}$ are the capacity and cost of using edge (i, j). The input and output links, I and O, carry a flow of $\sum_{i=1}^{N} H_i$ with a 0 edge cost.

Algorithm 2 Greedy Flow Graph Algorithm (GFGA)

```
1:  $\mathcal{C}_{r,t}$ = accumulated energy usage of RSU $r$ at time $t$.
2:  $\mathcal{S}_r$ = set of vehicles currently assigned to RSU $r$.
3:  $\mathcal{T}_r$ = set of time slots for which vehicles in $\mathcal{S}_r$ are within RSU $r$ coverage.
4:  for all $t \in \{0, 1, \ldots\}$ do
5:      for each vehicle $v$ that arrives to the system (at time $t$) do
6:          Assign $v$ to RSU $r = \arg\min_{i \in \mathcal{M}} \mathcal{C}_{i,t}$.
            (i.e., $\mathcal{S}_r \leftarrow \mathcal{S}_r \cup v$.)
7:          Update $\mathcal{T}_r$ to the union of time slots for which all vehicles in $\mathcal{S}_r$ are within RSU $r$ coverage.
8:          Solve ILP 7 to 10 for RSU $r$ using the vehicles in $\mathcal{S}_r$ for the time slots in $\mathcal{T}_r$. This can be done in time which is polynomial in $|\mathcal{T}_r|$ using a minimum cost flow graph. Update the value of $\mathcal{C}_{i,t}$ to account for the new assignments.
9:          Update the schedule for RSU $r$ using the solution generated in Step 8.
10:     end for
11:     Using the current schedule for each RSU, continue RSU-to-vehicle transmission (at time slot $t$).
12: end for
```

The form of ILP 7 to 10 is such that it can be solved in time complexity which is polynomial in the number of time slots using a minimum cost flow graph formulation [18]. This is shown for RSU r in Figure 3, where $G = (V, E)$ is defined by a set V of vertices (nodes) and a set E of edges (arcs) connecting the nodes. For each edge $(i, j) \in E$ there is a capacity $u_{i,j}$ that gives the maximum flow on the edge, and an associated cost, $c_{i,j}$, that denotes the cost per unit flow on that edge. These are written as ordered pairs, $(u_{i,j}, c_{i,j})$, on each graph edge in Figure 3.

The flow enters and exits the graph at dummy nodes S and D, respectively. The first column of nodes represents all vehicles in $\mathcal{S}_r$, where $N_r = |\mathcal{S}_r|$. The second column represents all time slots in $\mathcal{T}_r$, where $T_r = |\mathcal{T}_r|$. Each vehicle node has edges connected to the time slot nodes during which the vehicle is inside the RSU r coverage area. The capacity for an edge from the source S to a vehicle node is the residual communication requirement for vehicle j in time slots. The capacity for an edge from any time slot node to the destination D is 1 which prevents time slots from being used more than once. The edges between vehicle and time slot nodes also have a capacity of 1 which ensures that only one unit of transmission requirement can be assigned to a given time slot. The cost for using the edges originating from Node S or terminating at Node D is zero. Finally, the cost of the edges between the vehicle and time slot nodes is given by $\epsilon_{r,j,t}$ which is the energy cost of communication from RSU r to vehicle j at that time. Finding the minimum cost flow for graph G provides the minimum energy the RSU must consume to schedule vehicle transmission requirements for the given set of inputs. The Integrality Property Theorem [18] ensures that provided input flows and capacities are integer, the resulting minimum cost flow will also be integer. Since our vehicle to time slot edge capacities are 1, the resulting path flows are binary and give the optimum values for $K_{r,j,t}$.

Once the schedule for RSU r has been updated via Step 8 in Algorithm 2, this becomes the *active* schedule for that RSU. Finally, in Step 11 all RSUs will transmit if time slot t has been assigned.

IV. PERFORMANCE RESULTS

The performance of the proposed algorithms is investigated in this section. The theoretical bound for min-max RSU energy

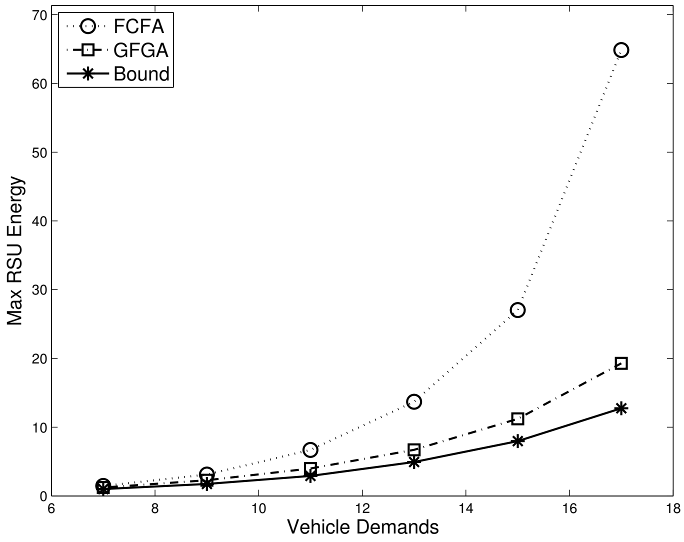

Fig. 4. Three Vehicle Classes. Light loading case with 1/15 vehicles/sec arrival rate. Vehicular speed classes of 20, 25 and 30 m/sec.

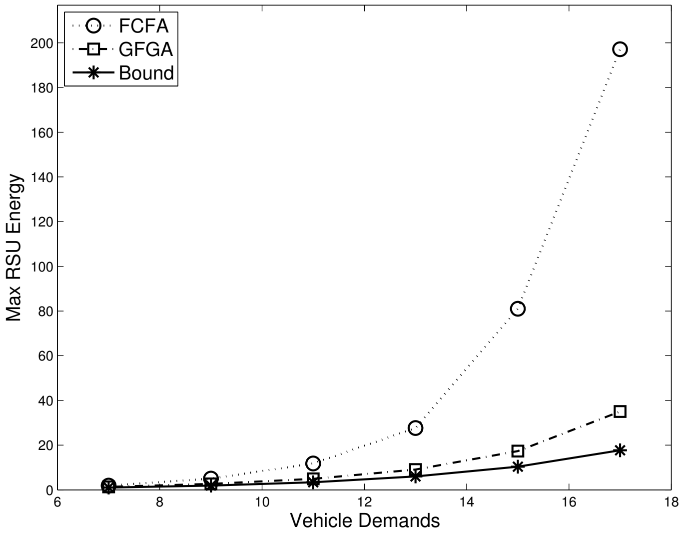

Fig. 5. Three Vehicle Classes. Heavy loading case with 2/21 vehicles/sec arrival rate. Vehicular speed classes of 20, 25 and 30 m/sec.

consumption as derived in Section II is referred to as *Bound* in the graphs and is compared to the online algorithms discussed in Section III. A highway environment is also assumed where vehicles are known to maintain relatively constant speed for long time periods. The models used include Poisson vehicle arrivals taken from References [15], [17] and [19]. The online algorithms use knowledge of vehicle position and associated estimates of downlink transmission energy costs. In this paper we assume that an accurate prediction of energy costs is possible based on a deterministic path loss scenario using a distance dependent exponential path loss model with a path loss exponent of $\alpha = 3$. For all the experiments we assume that $M = 4$ and that the RSU coverage radius is 1 Km. The value of the points in the graphs are normalized to the first point of the Bound graph in each figure.

In the first set of results we consider three classes of vehicles with the same arrival rate but different speeds of 20, 25 and 30 m/s, i.e., vehicles within each class have the same speed. The graphs show the maximum energy use for the RSUs (referred to as Max RSU Energy) as a function of varying vehicular demands. Figures 4 and 5 show a comparison of the algorithms under light and heavy loading scenarios, and the vehicle arrival rates are 1/15 and 2/21 vehicles/sec, respectively.

From these two figures it can be seen that, as one would expect, the maximum RSU energy increases as vehicular demands increase. This is due to having to serve the vehicles at less favourable locations further from the RSU because of both vehicular movement and contention for downlink time slots. It can also be seen that in both graphs the GFGA algorithm performs significantly better from a min-max RSU energy point of view. It also does well when compared with the optimum bound. In Figure 4 the worse-case performance difference is about 50% higher than the lower bound. This increases to about 90% in the heavy load case in Figure 5. Note that although we know that Bound is a true lower bound, its tightness is not known. In contrast, the FCFA algorithm performs significantly worse, with worse-case values of about 500% and 1000% times the lower bound for the light and heavy loading cases, respectively. However, as mentioned in Section III, FCFA is much less complex, and therefore much faster. From the two curves we can also see that if vehicle demands are very light, there is little value in the more complex algorithm.

In the second set of results, it is assumed that there are two classes of vehicles. The first class has a speed of 20 m/sec and the speed of the second class is varied over the values 20, 25, 30, and 35 m/sec. The results are plotted in Figures 6 and 7 which show the maximum RSU energy versus the second vehicle class speeds given above for both the light and the heavy vehicle demand cases. The vehicle arrival rates for the two classes in the light and heavy demand cases are 2/15 and 1/15, and, 4/21 and 2/21 vehicles/sec, respectively. As in the previous set of graphs, we see that increasing vehicle speeds leads to increased maximum RSU energy use since faster moving vehicles are in energy favourable locations for less time than slower moving vehicles. We can also see that the relative performance of the FCFA and GFGA schedulers is qualitatively similar to that found in the previous experiment. As before, we find that the more complex algorithm, i.e., GFGA, performs quite well compared with the lower bound and FCFA is much worse especially when the vehicle speeds are high. These results are representative of other comparisons that we have done for the two scheduling algorithms.

V. CONCLUSIONS

In this paper we have considered the issue of energy efficient scheduling in vehicular networks when there are multiple roadside units (RSUs) in tandem. The objective is to minimize energy use as much as possible while load balancing

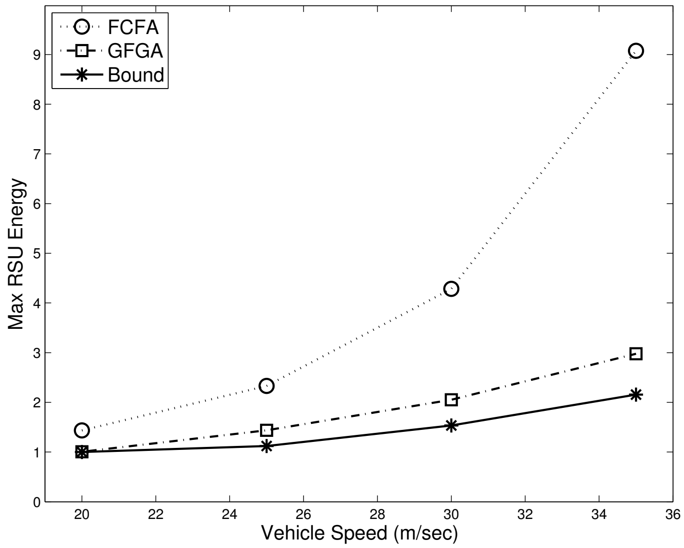

Fig. 6. Maximum Energy Use vs. Vehicle Speed. Two vehicle classes with 2/15 and 1/15 vehicles/sec arrival rates.

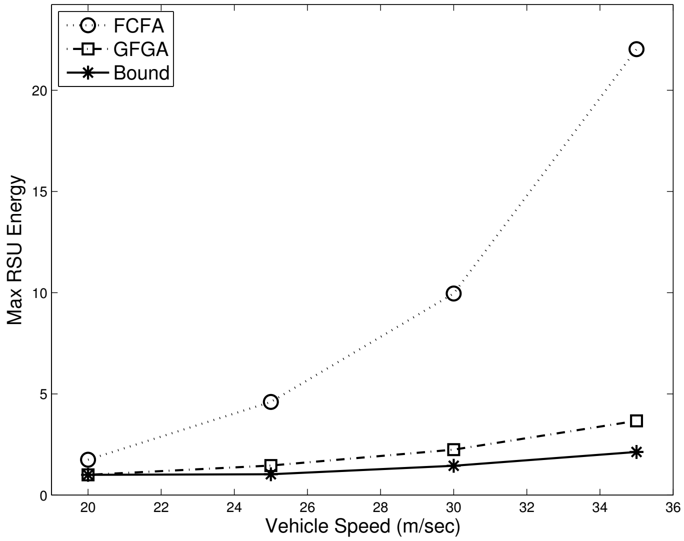

Fig. 7. Maximum Energy Use vs. Vehicle Speed. Two vehicle classes with 4/21 and 2/21 vehicles/sec arrival rates.

the energy costs across the roadside units. An offline lower bound was derived for the min-max energy usage of the roadside units for a given input sample function, which was used for comparisons with two proposed on-line scheduling algorithms. The first is a low complexity First-Come-First-Assigned (FCFA) scheduler which makes greedy RSU selections followed by a minimum energy time slot assignment. The second algorithm, the Greedy Flow Graph Algorithm (GFGA), makes the same RSU selection but reassigns time slots whenever a new vehicle is assigned to the same RSU. This is done using a locally optimum integer linear program that can be efficiently solved using a minimum cost flow graph. Results from a variety of experiments show that the GFGA algorithm performs well when compared to the energy lower bound, but deviates at higher values of vehicular demand and vehicle speed. In contrast, the FCFA scheduler performance is significantly worse when demands and vehicle speeds are high. The comparisons of the two algorithms give an indication of the trade-off between algorithm complexity and maximum RSU energy performance.

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