On/Off Sleep Scheduling in Energy Efficient Vehicular Roadside Infrastructure

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***Abstract*—Smart downlink scheduling can be used to reduce infrastructure-to-vehicle energy costs in delay tolerant roadside networks. In this paper we incorporate this type of scheduling into ON/OFF roadside unit sleep activity, to further reduce infrastructure power consumption. To achieve significant power savings however, the OFF-to-ON sleep transitions may be very lengthy, and this overhead must be taken into account when performing the ON state scheduling. We first incorporate the OFF/ON sleep transitions into a lower bound on energy usage that can be computed for given input sample functions. An online scheduling algorithm referred to as the Flow Graph Sleep Scheduler (FGS) is then introduced which makes locally optimum decisions about when to initiate new ON/OFF cycles. This is done by computing an estimate of the energy needed to fulfill known vehicle communication requirements with and without the OFF period. This calculation is efficiently done using a novel minimum flow graph formulation. Results from a variety of experiments show that the proposed scheduling algorithm performs well when compared to the energy lower bound. It is especially attractive in situations where vehicle demands and arrival rates are such that the energy costs permit frequent ON/OFF cycling.**

I. INTRODUCTION

In certain vehicular scenarios, the location of vehicles passing through roadside unit (RSU) radio coverage can be accurately predicted. When there is sufficient packet delay tolerance, smart schedulers can then use this information to reduce downlink infrastructure-to-vehicle energy communication costs [1]. This is done by scheduling traffic when vehicles are in favourable energy locations as illustrated in Figure 1. In the figure, vehicle v is shown at two different times and distances from the RSU, (t_1, d_1) and (t_2, d_2), respectively. Since $d_1 \gg d_2$, downlink communication with v may be far more preferable at time t_2 since the energy costs are likely to be significantly lower. Scheduling algorithms for this were first proposed in [1].

In this paper we show that this type of scheduling can be incorporated into aggressive ON/OFF sleep cycles to further reduce infrastructure power consumption. To achieve significant power savings however, certain RSU subsystems must be completely switched off, and this results in OFF-to-ON transitions which may be very lengthy. This overhead must be taken into account when scheduling downlink transmissions of the kind considered in [1]. We first formulate an integer program that incorporates ON/OFF sleep transitions into a lower bound on energy usage that can be computed for a given input sample function. This bound is used for comparisons with an online scheduling algorithm, which we call the Flow Graph Sleep Scheduler (FGS). FGS makes locally optimum decisions about when to initiate new roadside unit OFF cycles, by computing estimates of the energy needed to fulfill vehicle communication requirements with and without a new OFF period. These calculations are done using an efficient minimum cost flow graph formulation. Our results show that FGS performs well when compared to the energy lower bound and is especially attractive in situations where vehicle demands and arrival rates are such that the energy costs permit frequent ON/OFF cycling.

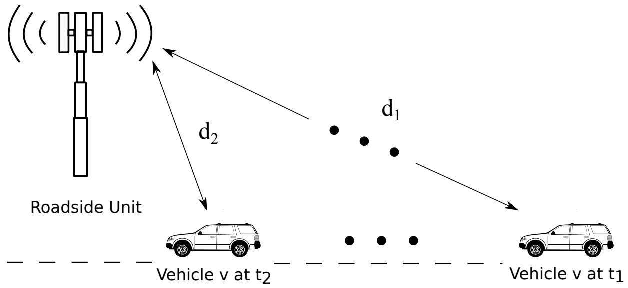

Fig. 1. Roadside Unit (RSU) Example. Vehicle v is shown at two different times, t_1 and t_2, and distances from the RSU, where $d_1 \gg d_2$. Communication at time t_2 is preferred in terms of RSU energy cost.

A. Related Work

Research in vehicular networks has recently included a wide variety of topic areas such as applications [2], ad hoc routing algorithms [3], authentication [4], and media access control performance [5]. For example, several studies have assessed the suitability of IEEE 802.11p for highway applications [6] and in [7][8][9], proxy vehicles are used to improve roadside unit utilization.

Studies have also considered the use of transmitter power control as a mechanism for trading off network connectivity and radio interference between vehicles [5] [10] [11]. The energy efficiency for VANETs however, has typically not been an issue, as vehicle engines provide virtually unlimited energy. Also, from the roadside infrastructure viewpoint, most previous work assumes urban settings where wired power is

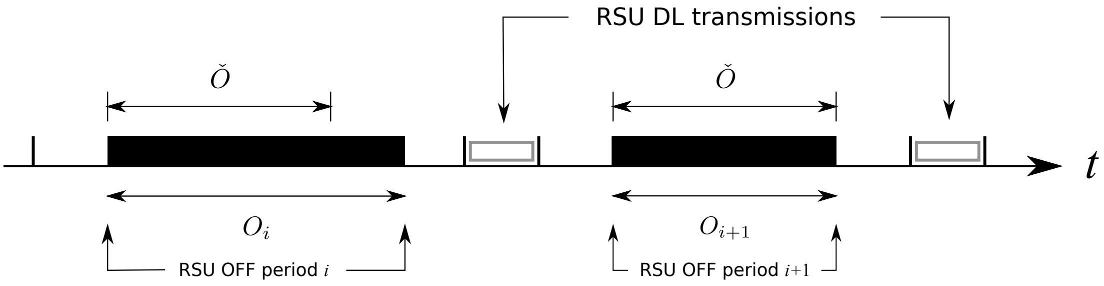

Fig. 2. Roadside Unit (RSU) Timeline Example. This example shows two RSU OFF periods of duration, O_i and O_{i+1}, respectively. The minimum OFF period, $\check{O}$, is shown to be 3 time slots in this example.

available at reasonable cost.

Traffic scheduling at the vehicular roadside units has been considered in [12] where simple schedulers were used based on vehicular data demand and message deadlines. In Reference [13] an optimization is used to maximize the throughput of a roadside unit given the locations and velocities of the vehicles. As in the previously referenced work however, the energy consumption for the RSU was not considered and this is the focus of our paper.

II. SYSTEM MODEL AND OFFLINE ENERGY BOUND

A roadside scenario is considered which consists of a single roadside unit (RSU) that serves passing vehicles, an example of which is given in Figure 1. In the figure, vehicles are shown traveling in the same direction but this is not a requirement. We assume that the RSU has a single radio which can only communicate with one vehicle at a given time.

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 the RSU coverage area. This can be accomplished in a variety of ways such as by using a short two-way handshake prior to user data packet transmission. An example of a time-line is given in Figure 2, which shows two RSU OFF periods with durations, O_i and O_{i+1}. During an OFF period the RSU is in a very low power consumption state and is unable to operate its radio subsystems.[1] Figure 2 also shows that there is a minimum duration OFF interval, denoted as $\check{O}$. This duration corresponds to the sum of the overhead required to transition from a fully active mode to a deep sleep mode, and to return to an active mode at the end of the OFF period. This overhead is included in the OFF state duration since the RSU is not functional during these transitions. However, as discussed below, there is an energy cost associated with these transitions. In the figure, O_{i+1} is shown as a minimum duration OFF interval, and $O_i > \check{O}$. It is assumed that when a vehicle v enters the coverage area of the RSU, it communicates its speed, direction and communication requirements, given by R_v bits, to the RSU. This is done using a medium access control protocol that permits the RSU to designate particular time slots, or mini-slots within particular time slots for uplink communication from newly arrived vehicles.

The objective is to schedule incoming vehicular downlink requests so that RSU energy use is reduced as much as possible. For this reason, the RSU prefers to communicate with nearby vehicles rather than more distant ones, as shown in Figure 1. To use this option however, requires that there is sufficient packet delay tolerance. The scheduling must also be done in a way which guarantees that the downlink packet reception requirements of the vehicles are fulfilled.

A. *Offline Energy Lower Bound*

Given an input sample function of arriving vehicles with known speed and traffic requests, a lower bound on the optimum energy scheduling is derived. We assume that there are N vehicles indexed by the set $\mathcal{N} = \{1, 2, \ldots, N\}$ 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_i is the downlink communication demand for vehicle i in bits. We define the following set of binary scheduling variables.

$$K_{i,t} = \begin{cases} 1 & \text{if the RSU transmits to vehicle } i \text{ in} \\ & \text{time slot } t, \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

$\mathcal{E}_t$ is defined to be the energy consumed by the RSU in time slot t when it is on the ON state, $\epsilon_{i,t}$ is the energy cost to transmit to vehicle i in time slot t, and ϵ_{I} is the energy consumed during a non-downlink transmission time slot when the RSU is in the ON state, i.e.,

$$\mathcal{E}_t = \sum_{i \in \mathcal{N}} \epsilon_{i,t}\, K_{i,t} + \epsilon_{\mathrm{I}}\, (1 - \sum_{i \in \mathcal{N}} K_{i,t}). \tag{2}$$

The first term calculates the energy used by the RSU to serve the downlink communication demands of the vehicles, while the second term computes the energy used by the RSU when it is in the idle/receive mode. Our objective is to assign time slots for downlink transmission and an ON/OFF schedule for the RSU that minimizes the total energy use over $\mathcal{T}$. We define

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[1] This low level of node activity is sometimes referred to as “deep sleep mode” where many node subsystems must be restarted before normal activity can resume. This is unlike the doze mode normally associated with air interfaces such as IEEE 802.11 where a node can reenter active mode almost instantly [14].

a binary variable, $\mathcal{O}_t$, as follows

$$\mathcal{O}_t = \begin{cases} 1 & \text{if the RSU is in the ON state in time} \\ & \text{slot } t, \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

We also define a binary variable X_t which is equal to 1 if the RSU transitions from the ON to the OFF state at time slot t. This can be written as

$$X_t = \begin{cases} 1 & \text{if } \mathcal{O}_{t-1} = 1 \text{ and } \mathcal{O}_t = 0, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

ϵ_X is defined to be the energy required by the RSU during the ON-to-OFF and its associated OFF-to-ON state transition. Using these definitions we can write the following integer program (IP) which gives a lower bound on the RSU energy required.

$$\begin{aligned} \underset{K_{i,t},\, \mathcal{O}_t}{\text{minimize}} \quad & \sum_{t\in\mathcal{T}} \Big(\sum_{i\in\mathcal{N}} \epsilon_{i,t}\, K_{i,t} + \epsilon_{\mathrm{I}}\, (1 - \sum_{i\in\mathcal{N}} K_{i,t})\Big)\, \mathcal{O}_t \\ & + \epsilon_X \sum_{t\in\mathcal{T}} X_t & (5) \\ \text{subject to} \quad & \sum_{t\in\mathcal{T}} K_{i,t} = \lceil R_i/B \rceil, \qquad \forall i \in \mathcal{N} & (6) \\ & \sum_{i\in\mathcal{N}} K_{i,t} \le 1, \qquad \forall t \in \mathcal{T} & (7) \\ & K_{i,t} \le \mathcal{O}_t, \qquad \forall i \in \mathcal{N}, t \in \mathcal{T} & (8) \\ & X_t \le \mathcal{O}_{t-1}, \qquad \forall t \in \mathcal{T} & (9) \\ & X_t \ge \mathcal{O}_{t-1}\,(1 - \mathcal{O}_t), \qquad \forall t \in \mathcal{T} & (10) \\ & X_t \le 1 - \mathcal{O}_{t-1}\, \mathcal{O}_t, \qquad \forall t \in \mathcal{T} & (11) \\ & \sum_{l=0}^{\check{O}-1} \mathcal{O}_{t+l} \le M(1 - X_t), \qquad \forall t \in \mathcal{T} & (12) \\ & K_{i,t} \in \{0,1\}, \qquad \forall i \in \mathcal{N}, t \in \mathcal{T} & (13) \\ & \mathcal{O}_t, X_t \in \{0,1\}, \qquad \forall t \in \mathcal{T} & (14) \end{aligned}$$

In IP 5 to 14, the objective function is the total energy used by the RSU. The first line in Equation 5 is the energy expenditure from Equation 2 summed over those time slots when the RSU is in the ON state. The second line is the energy consumed during the OFF/ON transitions after awakening the RSU, i.e., the summation over all X_t gives the number of OFF periods that the RSU incurred. Since the RSU is in a deep sleep during the OFF periods, we assume that power consumption associated with this is negligible compared with the other states, except for the aforementioned transition energy. Constraint 6 ensures that each vehicle communication requirement is fulfilled by summing the appropriate values of $K_{i,t}$ and Constraint 7 ensures that at most a single packet is allocated to each time slot. Constraint 8 makes sure that the RSU can only assign time slots when it is in the ON state. Constraints 9 to 11 are used to properly define the X_t variables as given in Definition 4 and an example of this is shown in Figure 3. By definition, X_t is only equal to 1 when there is a $1 \rightarrow 0$ transition in $\mathcal{O}_t$. From Constraints 9 to 11, when $(\mathcal{O}_{t-1}, \mathcal{O}_t) = (1, 0)$ as shown in Figure 3, $X_t \le 1$, $X_t \ge 1$, and $X_t \le 1$, which gives $X_t = 1$. All the other combinations for $(\mathcal{O}_{t-1}, \mathcal{O}_t)$ give $X_t = 0$ as required by Definition 4. Constraint 12 ensures that when there is an ON/OFF transition, the RSU cannot be active for at least $\check{O}$ time slots, i.e., the time which is required to re-awaken the RSU from OFF mode. When $X_t = 1$, Constraint 12 makes sure that at least the next $\check{O}$ time slots are not usable. In this constraint, M is a constant where $M \ge \check{O}$. Constraints 13 and 14 define the binary variables.

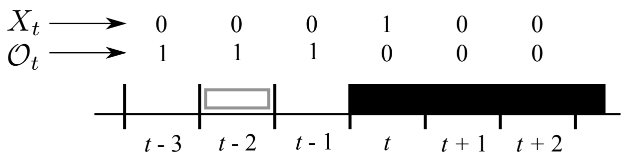

Fig. 3. Roadside Unit (RSU) ON/OFF Transition Example.

IP 5 to 14 contains binary quadratic terms in the objective function and in Constraints 10 and 11. But because they are products of single binary variables, these equations can be linearized by introducing supplementary variables [15]. This permits its solution using integer linear programming methods, such as branch and bound algorithms. These results are used for comparisons with an online algorithm to be introduced in the next section.

III. ONLINE SCHEDULING ALGORITHMS

The optimization derived in Section II gives a lower bound on the downlink RSU energy needed to satisfy vehicular packet requirements. In order to compute the bound, the energy costs associated with a given packet transmission are used. Although it is difficult to precisely know this information in real-time situations, in certain scenarios excellent estimates of this cost can be made [16][17]. Accordingly, we consider a highway scenario where vehicles may travel at different speeds, but maintain their own speed throughout the RSU coverage areas [18]. When vehicles enter the RSU radio coverage area they announce their location, direction and speed, which is information that can be used to accurately compute future energy transmission costs. This is done assuming distance dependent exponential path loss propagation [16][17]. If the RSU is in the OFF state when a vehicle arrives, we assume that this announcement occurs when the RSU returns to the ON state.

A. Flow Graph Sleep Scheduler (FGS)

In the FGS algorithm, the RSU makes locally optimum decisions about when to initiate OFF periods. This is done by computing an estimate of the energy needed to fulfill known vehicle communication requirements both with and without initiating a new OFF period of duration T_s time slots, which is given as a parameter. These computations are made using all currently available vehicular information and remaining backlog, and is recomputed in each time slot when the RSU is ON. The algorithm is shown in Algorithm 1 and is described in detail as follows.

Algorithm 1 Flow Graph (FGS) Scheduler

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1: $\mathcal{V}_t$ = the set of vehicles with unfulfilled backlog within RSU coverage at time $t$.
2: $\mathcal{T}_t$ = the union of all time slots for which vehicles in $\mathcal{V}_t$ are within RSU coverage at time $t$.
3: $S_t^a$ = the active schedule at time $t$.
4: for all $t \in \{0, 1, \ldots\}$ do
5:     if RSU state is ON then
6:         $S_t$ = solve(ILP 15 to 18, $\mathcal{V}_t$, $\mathcal{T}_t$).
7:         $\mathcal{T}'_t \leftarrow \mathcal{T}_t - \{t' \mid t \leq t' \leq t + T_s\}$
8:         $S'_t$ = solve(ILP 15 to 18, $\mathcal{V}_t$, $\mathcal{T}'_t$).
9:         if energy($S_t$) $\leq$ energy($S'_t$) then
10:            $S_t^a = S_t$.
11:        else
12:            $S_t^a = S'_t$.
13:        end if
14:        Depending on $S_t^a$, either continue RSU-to-vehicle transmission or enter OFF mode (at time slot $t$).
15:    else
16:        if RSU OFF period has expired then
17:            Set RSU state to ON.
18:        end if
19:    end if
20: end for
```

As shown in Step 5 at time t, when the RSU is in the ON state, it first finds a schedule, S_t, needed to serve all currently known vehicular backlog. This is done in Step 6 by solving ILP 15 to 18 (introduced below) using the vehicles currently in RSU coverage, i.e., $\mathcal{V}_t$, for the time slots in $\mathcal{T}_t$, which is defined to be the union of all time slots for which vehicles in $\mathcal{V}_t$ are within RSU coverage at that time. This ILP can be efficiently solved using a minimum cost flow graph [1][15], and is discussed in detail below. In Steps 7 and 8 we again solve ILP 15 to 18 but *assuming* an OFF period of duration T_s starting at time slot t. This is done by using the same known vehicular inputs but by removing those time slots which are used for sleeping the RSU. This gives the set of time slots $\mathcal{T}'_t$, and results in schedule S'_t.

The ILP used in Steps 6 and 8 is similar to ILP 5 to 14 except that optimization of the OFF period is not included. It solves for the minimum energy schedule for the RSU using the currently available inputs at time t, namely $\mathcal{V}_t$ and $\mathcal{T}_t$, and is given as follows.

$$\underset{K_{i,t}}{\text{minimize}} \quad \sum_{t \in \mathcal{T}_t} \sum_{i \in \mathcal{V}_t} \epsilon_{i,t} \, K_{i,t} \tag{15}$$

$$\text{subject to} \quad \sum_{t \in \mathcal{T}_t} K_{i,t} = \lceil \widetilde{R_i}/B \rceil, \quad \forall i \in \mathcal{V}_t \tag{16}$$

$$\sum_{j \in \mathcal{S}_r} K_{i,t} \leq 1, \quad \forall t \in \mathcal{T}_t \tag{17}$$

$$K_{i,t} \in \{0, 1\}, \quad \forall \{i \in \mathcal{V}_t, t \in \mathcal{T}_t\} \tag{18}$$

Constraint 16 satisfies the *residual* (i.e., remaining un-served) transmission requirement for vehicle i, given by $\widetilde{R_i}$. ILP 15 to 18 is in a form that can be solved in time complexity which is polynomial in the number of time slots, i.e., $|\mathcal{T}_t|$, using a minimum cost flow graph [1][15]. This is shown in Figure 4, 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. Each edge (i, j) also has an associated cost, $\epsilon_{i,t}$, that denotes the cost per unit flow on that edge. These are written as ordered pairs, $(u_{i,t}, \epsilon_{i,t})$, on each graph edge in Figure 4.

The flow enters and exits the graph at dummy nodes S and D, respectively. The first column of nodes represents all vehicles in $\mathcal{V}_t$, where we have assumed that $N_t = |\mathcal{V}_t|$. The second column represents all time slots in $\mathcal{T}_t$, where $T_t = |\mathcal{T}_t|$. Each vehicle node has edges connected to the time slot nodes during which the vehicle is inside the RSU coverage area. The capacity for an edge from the source S to a vehicle node is the residual communication requirement for vehicle i in time slots, denoted by

$$H_i \triangleq \lceil \frac{\widetilde{R_i}}{B} \rceil. \tag{19}$$

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 a vehicle i and the time slots 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 $\epsilon_{i,t}$ which is the energy cost of communication to vehicle i at time t. 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 [15] ensures that provided input flows and capacities are integer, the resulting minimum cost flow with also be integer. Since our vehicle to time slot edge capacities are 1, the resulting flows are binary and gives the optimum values for $K_{i,t}$.

In Algorithm 1, once the schedules for the RSU have been updated in Steps 6 to 8, the minimum energy option is assigned as the active schedule, S_t^a, in Step 9. When the RSU is in the OFF state, Steps 16 and 17 are used to test if the RSU should return to the ON state.

IV. PERFORMANCE EVALUATION

In this section we present performance results for the proposed scheduling algorithm introduced in Section III. The lower bound for RSU energy consumption that was derived in Section II is also included and is referred to as *Bound* in the graphs. A highway environment is also assumed where vehicles maintain constant speeds for relatively long time periods and as in References [16][18][19] we assume Poisson process vehicle arrivals. The online algorithms use knowledge of vehicle position and estimates of downlink transmission energy costs. In our results we assume that an accurate prediction of energy costs is possible based on a deterministic

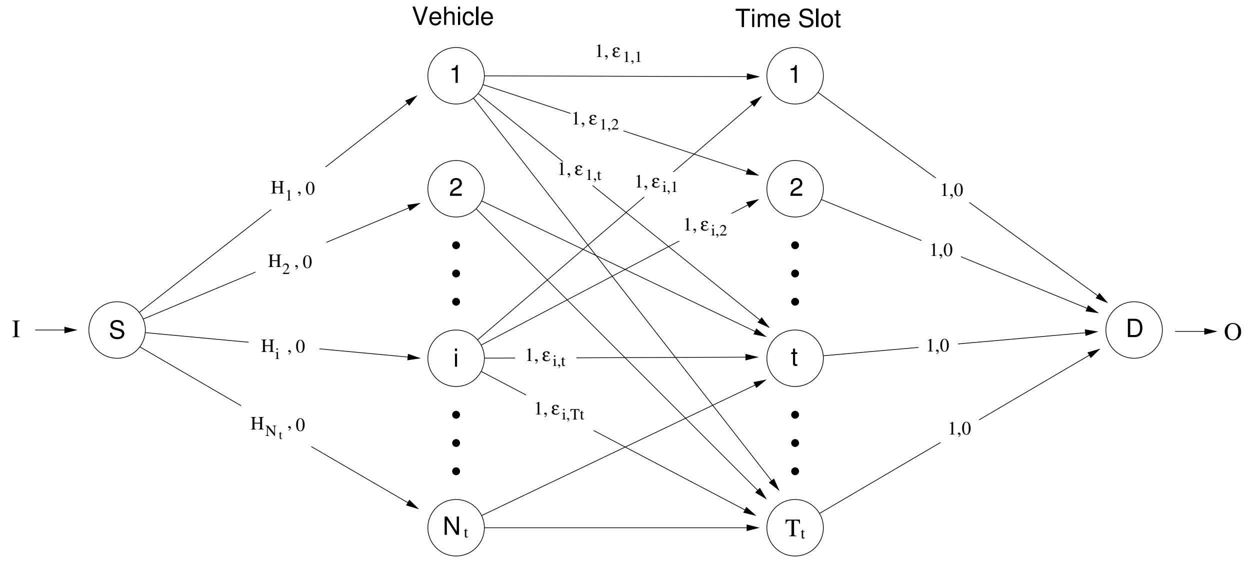

Fig. 4. Minimum Energy Flow Graph Scheduler. Each edge is labeled with an ordered pair, $(u_{i,t}, \epsilon_{i,t})$, where $u_{i,t}$ and $\epsilon_{i,t}$ are the capacity and cost of using edge (i, t). The input and output links, I and O, carry a flow of $\sum_{i=1}^{N} H_i$ with a 0 edge cost.

path loss scenario using a distance dependent exponential path loss model.

In Figures 5 and 6 we plot the total RSU energy use versus vehicular demand for the FGS scheduler with different values of the T_s parameter. Also included in the graphs are the results that would be obtained without ON/OFF scheduling (i.e., the "FGS, ON" curve) but still using the flow graph scheduler for slot allocation. We have also plotted the analytic lower bound formulation from Section II. The other parameters used are, $\epsilon_{\mathrm{I}} = 100$, $\epsilon_X = 500$, and $\check{O} = 5$ time slots. The low and high vehicular arrival rates are 1/100 and 1/20 vehicles/sec, respectively.

In Figure 5 the vehicular arrival rate is low and it can be seen that there are significant improvements in energy use, with the best performance obtained when $T_s = 30$. When T_s is decreased to 10 or increased to 50 the results become worse. The reason for this is that when T_s is too small, the repeated instances of ON/OFF cycles incurs energy penalties which are proportionately higher than would be the case if longer OFF periods are used. However, this effect does not continue indefinitely as can be seen for the $T_s = 50$ case. Instead, when T_s is too large, the RSU remains in the OFF state too long and is unable to schedule vehicular time slots at the best times. Also, even when this is not the case, the RSU is forced to remain in the ON state for lengthy time periods while vehicles move into more favourable positions. This is the reason that the curve for $T_s = 50$ does increasingly worse as the vehicle demand increases.

It can be seen in general that as the vehicle demand increases, there is less opportunity for ON/OFF cycling and as a result, for large enough vehicular demands, FGS without sleeping performs the same as in the different T_s cases. In this case the curves become much closer to the Bound, which indicates that the flow graph scheduler is doing a good job of allocating time slots. At the extreme left of the graph it can be seen that the FGS performance is quite a bit above that of Bound, suggesting that a scheduler with adaptive sleep periods may perform better. This is not certain however, since the Bound has non-causal knowledge of future vehicle arrivals and adjusts its sleep periods accordingly. Figure 6 uses the same parameters as Figure 5 except that the vehicle arrival rate is higher. This results in increased contention and less opportunity for RSU sleeping. However, the same trends occur.

In Figure 7 we show another example with the same parameters as in Figure 5 except that we have significantly decreased the OFF/ON energy cost to $\epsilon_X = 100$. It can be seen that doing so makes the value of OFF/ON cycling much more attractive resulting in much improved energy performance compared with the FGS algorithm without deep sleeping. As before, if we significantly increase the vehicle arrival rate, the value of sleep cycling becomes less as was the case in Figure 6.

V. CONCLUSIONS

This paper we has considered the problem of energy efficient vehicular roadside unit scheduling. OFF-to-ON roadside unit sleep transitions have been incorporated into minimum energy cost downlink transmission scheduling. An integer program was derived for this case that gives a lower bound on energy use that can be achieved for a given input sample function, and an online scheduling algorithm referred to as the Flow Graph Sleep Scheduler (FGS) was introduced. In the proposed FGS algorithm, the RSU makes greedy optimum OFF period scheduling decisions. This is done by computing an estimate of the energy needed to fulfill known vehicle communications requirements without initiating an OFF period, and by making a similar computation based on initiating an OFF period. These are recomputed in each time slot. Our results showed that FGS performs well when compared to the

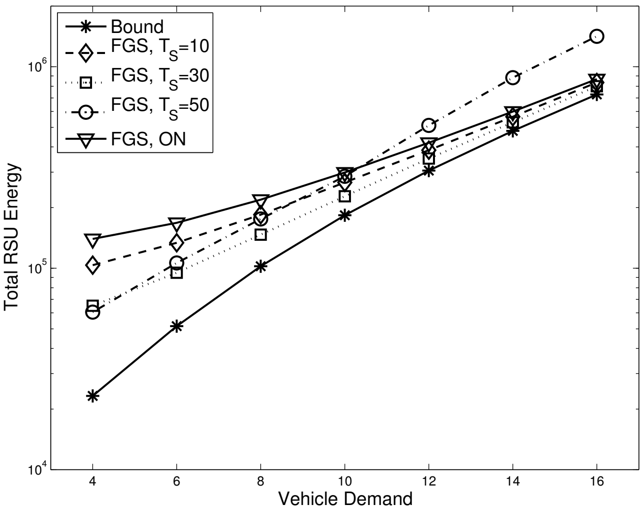

Fig. 5. Total RSU Energy (J) vs. Vehicular Demand (time slots). $\epsilon_I = 100$, $\epsilon_X = 500$, and $\check{O} = 5$ time slots. Low vehicular arrival rate case.

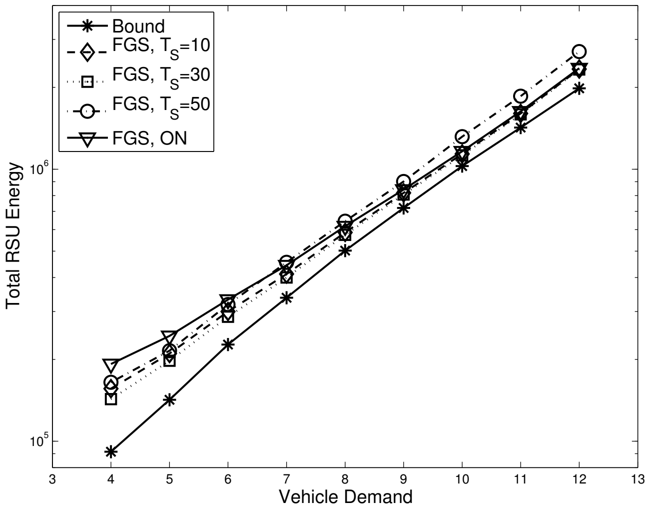

Fig. 6. Total RSU Energy (J) vs. Vehicular Demand (time slots). $\epsilon_I = 100$, $\epsilon_X = 500$, and $\check{O} = 5$ time slots. High vehicular arrival rate case.

energy lower bound and is especially useful in situations where vehicle demands and arrival rates are such that the energy costs permit frequent ON/OFF cycling.

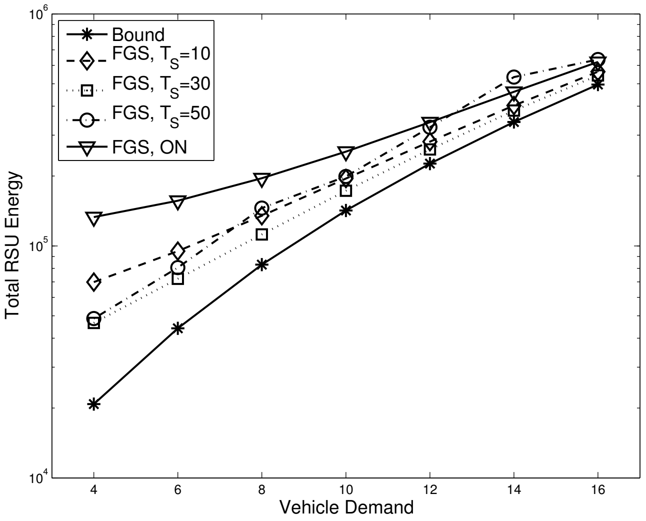

Fig. 7. Total RSU Energy (J) vs. Vehicular Demand (time slots). $\epsilon_I = 100$, $\epsilon_X = 100$, and $\check{O} = 5$ time slots. Low vehicular arrival rate case.

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