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Standalone Green Cache Points for Vehicular Content Distribution Networks

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Abstract - **With the rapid growth of interest in media-rich user experience, content distribution networks (CDNs) gained considerable attention. Since, most of the energy is consumed by cache points (CPs) and the associated equipment, it is imperative to deploy fewer number of CPs or switch off as many as possible to save energy. This results in degraded quality of service (QoS). It is an usual dimensioning technique to optimise the number and locations of caching points (CPs) of a content distribution network (CDN), where the objective is to reduce operational energy. In this paper, we reduce non-renewable energy consumption (carbon footprint) by introducing renewable grid energy (in the form of wind energy) and adaptive CPs. Further, we propose algorithms for provisioning high number of simultaneous downloads, which reduce overall waiting time and number of dropped request of city vehicular users. The end result is substantial improvement in quality of service (QoS). The proposed CPs save 100% grid energy during the whole day while fulfilling content demand in a city vehicular environment.**

Keywords — Content caching; content distribution network; green energy; optimization; quality of service; vehicular networks.

I. INTRODUCTION

Modern vehicles are increasingly equipped with on-board computing devices. While car phones, on-board Internet and Bluetooth are existing examples of wireless communication technologies in modern vehicles, corporate sectors and scientists are aiming towards the implementation of content reach in-car entertainment along with ultra-low latency safety applications that are able to foresee hazardous road conditions.

In the above context, much attention has been drawn in Content Distribution Networks (CDNs), which does content catching to reduce end-to-end (e2e) delay and network congestion thereby improving download rate. The problem of congestion can be settled by directing a BS's traffic to nearby Cache Points (CPs) with higher capacities—an approach that significantly lowers the downloading time as well. Additionally, drawing content closer to end users considerably reduces energy consumption since road-side caches function at locations with weaker BS signals [1, 2]. The above advantages warrant more attention to be paid to content caching in vehicular networks. It is well known that the information and communications technology (ICT) sector [3] presently produces 2%-2.5% of the world carbon emissions, a number which is predicted to significantly grow in the next few years. Concerns over carbon footprints, coupled with the depleting fuel resources, have led to serious re-evaluations of ICT architecture.

In this paper, we propose energy efficient content delivery through cache points in city vehicular network. We consider both non-adaptive and adaptive CPs, which are powered by non-renewable and renewable grid (wind) energy. To start with we have taken a model city as shown in Figure 1 and optimized the number of CPs installed in the city. In adaptive CPs, the number of simultaneous download is based on the amount of available renewable energy. To reduce network energy consumption, as a first step, we previously optimized the number and location of the CPs to support content delivery at high data rates. Then, we study both non-adaptive and adaptive cache points in the context of non-renewable and renewable energy. Our contributions in this paper are the followings:

We develop (i) Mixed Integer Linear Programming model (MILP) with non-renewable energy sources for non-adaptive CPs, (ii) Heuristic with non-renewable energy sources for non-adaptive CPs, (iii) MILP model with renewable energy sources for adaptive CPs, (iv) Heuristic with renewable energy sources for adaptive CPs, and (iv) MILP model with renewable energy sources for non-adaptive CPs, to compare and study the performance results in detail.

II. VEHICULAR CITY MODEL

To analyse the performance of the cache points, a simplistic model city is adopted in this paper as shown in Figure 1.

The model consists of 16 junctions and 48 roads, where each junction has 4 exits [4]. We have corroborated typical traffic statistics of a UK city, on which statistical analysis has been carried out in order to capture traffic patterns throughout an office day. Our study includes data from October 15, 2009, and limits itself to a 9 km^2 coverage area, which means a maximum number of 500 vehicles per hour. The hourly vehicular flow is shown in Figure 2, where the peak traffic is observed in business and afternoon (16:00-18:00) hours.

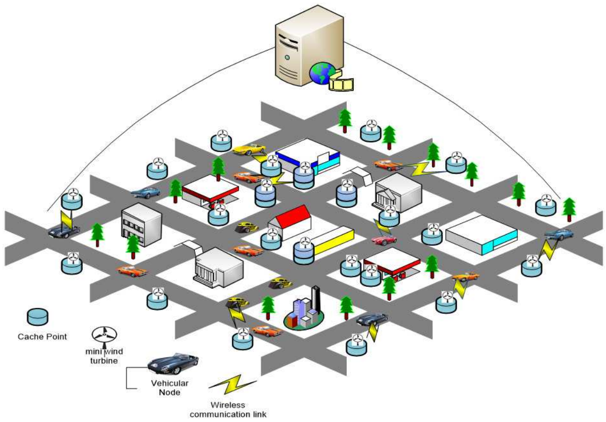

Figure 1 : City vehicular network.

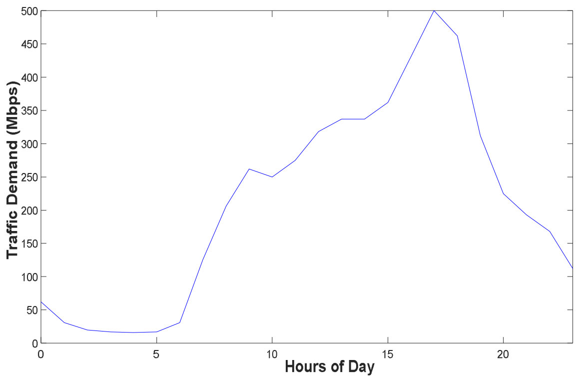

Figure 2: Hourly vehicular traffic flow.

III. Wi-Fi Point Based Content Distribution Network

We propose a set of CPs with media-rich contents closer to the vehicles for decreasing the obstruction in the communication path between the server and the vehicles. Due to the limited storage capacity of the CPs, only the most popular media contents are stored. Instances of such popular content include store advertisements in a city, movie trailers, videos on free parking spaces and BBC iPlayer and YouTube videos. Higher download rates and better energy efficiency are expected to be achieved by such a setup employed for coverage and voice services (i.e. low download rates) and CPs are continuously activated and deactivated to save energy [5].

We plan for 192 candidate sites (CSs) throughout the city with each road having four CSs. The candidate sites are the potential places where the CPs can be installed. This provides the basis of optimisation of the number and location of such CPs. Each CP is implemented with an IEEE 802.11p radio transceiver unit having data rates varying between 3 Mb/s-18 Mb/s depending on the range of communication and the reliability of the channel [6]. According to [6], the typical range of communication in vehicular networks can reach up to 300 meters (radius). However, the current study assumes a range of 100 meters to decrease the communication path between the servers and the vehicles. This leads to higher number of CPs. Each CP is further equipped with a storage disk for a maximum of 50 content files, a microcontroller acting as an interface with application coordinating requests and ordering files, and a MAC algorithm unit (e.g. Vehicular Content Download Algorithm VCDA[2])

A content file would be downloaded from multiple rather than single CPs during the entire journey of a vehicle. Each file is divided into a number of smaller pieces to avoid interruption during handover, where the complete file download is finished when a vehicle has downloaded all the pieces from different CPs. For instance, a CP with a 100 meters transmission range (200 meters in diameter) and a vehicle with a maximum speed of 13 m/s would lead to a case where the vehicle remains within the CP range for at least 16 seconds. Assuming a download rate of 3 Mb/s, 33 pieces of 6 MB each can be downloaded in 16 seconds. The traffic is generated by the moving vehicles in the form of requests for pieces of a video content. The video content is replicated in all CPs. The maximum number of simultaneous connections (piece downloads) is computed from the available wind energy at each CP, which varies with time.

IV. Green Energy

Due to the ecological and economic factors, introducing energy efficiency in information and communication technology (ICT) sector has become mandatory in modern days. According to [7] , the information and communication technology (ICT) sector currently emits 2-2.5% of the global carbon emissions. This drives the motivation for green and energy efficient content distribution network (CDN).

A. *Wind Energy Profile*

The United Kingdom is considered to be the world's sixth largest producer of wind energy [8]. The raw wind data is comprised of hourly wind speeds for the whole of 2015 measured at one of their monitoring sites in a typical UK cities (obtained from the UK air information resource (AIR) database provided by the Department for Environment, Food and Rural Affairs [9]). The wind energy obtained from the wind speed depends upon several factors related to power grid, transmission and distribution. Thus, we obtained a very simplistic model of the hourly average wind energy as below.

B. *Mathematical Model*

Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy that can be distributed. This includes a gross loss incurred during various stages of generation, transmission and distribution. The wind energy harnessed depends on the wind speed and the swept area of the turbine [10]. The following table shows the definition of various variables used in this model.

Table 1 : List of Notations.

E	Kinetic Energy (J)
ρ	Density (kg/m^3)
m	Mass (kg)
A	Swept Area (m^2)
v	Wind Speed (m/s)
C_P	Energy Coefficient
$\frac{\mathrm{dm}}{\mathrm{dt}}$	Mass flow rate (kg/s)
x	distance (m)

$\frac{dE}{dt}$	Energy Flow Rate (J/s)

The kinetic energy of a mass in motion is:

$$E = \frac{1}{2} m v^2 \quad (1)$$

The energy in the wind is given by the rate of change of energy [10]:

$$P = \frac{dE}{dt} = \frac{1}{2} v^2 \frac{dm}{dt} \quad (2)$$

As mass flow rate is given by:

$$\frac{dm}{dt} = \rho A \frac{dx}{dt} \quad (3)$$

And the rate of change of distance is given by:

$$\frac{dx}{dt} = v \quad (4)$$

We get:

$$\frac{dm}{dt} = \rho A v \quad (5)$$

Hence, from equation (2), the energy can be defined as:

$$P = \frac{1}{2} \rho A v^3 \quad (6)$$

Wind turbines cannot convert all the kinetic energy of the wind into mechanical energy turning a rotor. C_P is the coefficient of performance of the wind turbine which accounts for the decrease in the actual energy harnessed from the wind due to several factors such as, rotor, blade, frictional losses. Therefore,

$$P_W = \frac{1}{2} C_P \rho A v^3 \quad (7)$$

The relationship between generated energy and wind speed is nonlinear. This means, we cannot simply use the average wind speed to determine the average energy generated. Therefore, rewriting the generated energy in terms of average values, we obtain:

$$P_{avg} = (\frac{1}{2} C_P \rho A v^3)_{avg} = \frac{1}{2} C_P \rho A v^3_{avg} \quad (8)$$

In probabilistic terms, the average value of v^3 is

$$v^3_{avg} = \sum_i [v_i^3 \, P(v = v_i)] \quad (9)$$

We obtain the average wind generated energy in a 24 hour period by considering the wind speeds at each hour for the whole year. Figure 3 shows the hourly average wind energy in a typical UK site. The wind energy conversion parameters are presented in Table 2.

Table 2 : System parameters.

Parameters	Values
Propeller length in diameter (D_{jt})	0.5 m [11]
Swept area (A)	0.2 m^2
Coefficient of performance (C_P)	0.45 [11]
Air density (ρ) at 150^0 C	1.225 kg/m^3 [9]

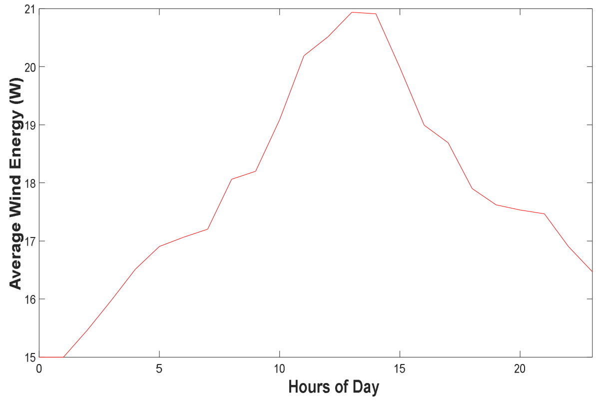

Figure 3: Average wind energy in a typical UK site.

V. A LINEAR PROGRAMMING MODEL

This study would focus on the possibility of having an energy-efficient content distribution network in a city. In order to optimise the number of required CPs, we developed a mixed integer linear programming (MILP) model which minimises total power consumption of the CPs while serving varying levels of traffic demand for different vehicular flows at each hour of the day. The number of sets, parameters and variables are defined in Table 3 is used in the model.

Table 3 : List of Notations.

Notations	Values
Parameters:	
$P\_CP_{OP\_Max\_ct}$	Maximum operational power consumption of a CP i.e. 20 W [12]
$P\_CP_{OP\_Min\_ct}$	Ceiling($P\_CP_{OP\_Max\_ct}$/1.3548) = 14 W [13]
$P\_CP_{TX\_Max\_ct}$	Maximum transmitter power consumption of CP *c* at time *t* $P\_CP_{OP\_Max\_ct} - P\_CP_{OP\_Min\_ct}$ = 6 W [13]
$P\_CP_{TX\_Min\_ct}$	Minimum transmitter power consumption of CP *c* at time *t* i.e. 1 W
P_{Wct}	Average of wind power at CP *c* at time *t*
P_{REct}	Renewable part of power consumption of CP *c* at time *t*
P_{NREct}	Non-renewable part of power consumption of CP *c* at time *t*
A	Large number for MILP constraint, set to 10000 here
Variables:	
$P\_CP_{TX\_ct}$	Power transmitting consumption of CP *c* at time *t*
$P\_CP_{RX\_ct}$	Receiver consumption power of CP *c* at time *t*, i.e. 0 in our case
$P\_CP_{TX\_ADP\_ct}$	Adaptive transmission power by CP *c* at time *t*
K_{ct}	Balance variable between operational power and average available renewable power
α_{ct}	Equals 1 if CP *c* is on, equals 0 otherwise
β_{ct}	Equals 0 if Renewable energy is adequate for power consumption of CP, equals 1 otherwise
δ_{cjt}	Equals 1 if CP *c* is transmitting content to Vehicle *j*, equals 0 otherwise
N_{d_ADP}	Adaptive number of simultaneous downloads (i.e. 0~10)
Indices:	
c	Index of caching point (CP)
j	Index of test point (Vehicles)
t	Index of time point (T)

The contents are considered to be already distributed through the internet in the CPs. Hence, the vehicles do not generate content and upload to the CPs. The data rate is fixed at maximum. The number of simultaneous connections of a CP can be defined as:

$$N_{d\_ADP} = \frac{B_{Max}}{Data\ Rate} \quad (10)$$

Where, B_{Max} is the maximum bandwidth in Mbps.
Therefore, energy consumption per bit is given by

$$P\_CP_{TX\_ADP\_ct} / B_{Max} \times 10^6$$

a) All Renewable Sources with non-adaptive CPs (RE + NonADP- CPs)

For this setup, we assume that the CDN does not have access to non-renewable power. Thus, the traffic demand could only be served, whenever the available wind power is sufficient. Otherwise, the CP would stay switched OFF. The objective is to minimise number of CPs to minimize energy consumption. The following constraints are incorporated into the model to switch OFF the CPs whenever renewable energy is inadequate:

$$P_{NREct} = P\_CP_{TX\_Max\_ct} + P\_CP_{OP\_Min\_ct} - P_{REct} \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (11)$$

$$P_{NREct} \geq \ \beta_{ct} \quad (12)$$

$$\forall c\epsilon CP, \forall\ t\epsilon T P_{NREct} \leq \ \beta_{ct} \times A \quad (13)$$

$$\forall c\epsilon CP, \forall\ t\epsilon T$$

Equations (11-13) ensure that the model does not consume any non-renewable energy. If the renewable power consumption is lower than the maximum power required to switch ON a CP, $\beta_{ct} = 1$, else $\beta_{ct} = 0$.

$$\sum_{j\epsilon Np[c]} \delta_{cjt} \times (1 - \ \beta_{ct}) \ \geq \ \alpha_{ct} \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (14)$$

$$\sum_{j\epsilon Np[c]} \delta_{cjt} \times (1 - \ \beta_{ct}) \ \leq \ \alpha\_ct \ \times A \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (15)$$

Equations (14) and (15) ensure that if there is a connection between CP *c* and TP *j* at time point *t* and renewable power is adequate, then CP *c* is switched ON ($\alpha_{ct} = 1$).

b) All Renewable Sources with Adaptive Capacity of CPs (RE + ADP-CPs)

In the previous setup (a), there may have been instances where traffic demand could not be served. However, by introducing a simplistic (linear) relationship between transmission power of a CP and the capacity of a CP, total traffic demand could be served by all renewable wind power. This, however, would be achieved at higher number of CPs, where a lower capacity for CPs was adapted according to the lower wind power. Note that to switch ON a CP, minimum operational power (i.e.14 W [12]) is required, hence only transmitting power can be varied depending upon the available wind power.

Since, in this setup, our aim is to serve traffic demand with only renewable energy while switching ON the minimal number of CPs, we maximise the transmitting power of each CP so that the maximum capacity of CPs (in terms of simultaneous downloads), dependent upon the available wind power, could be achieved.

The objective function still is minimising the number of CPs to minimise usage of energy and serving all traffic demand. To support maximum download rate, capacity of CP is adapted by the transmission power available through wind energy. Considering equation (10), adaptive number of simultaneous downloads is calculated as:

$$N_{d\_ADP} = (\ P\_CP_{TXct} \times N_{d\_Max}\ ) / P\_CP_{TX\_Max\_ct} \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (16)$$

which takes the effect of adaptive transmission power into account. To incorporate the effect of N_{d_ADP}, we introduce the constraint:

$$\sum_{j\epsilon Np[c]} \frac{\lambda_{cjt}}{Data\ Rate} \leq N_{d\_ADP} \quad \forall\ c\epsilon CP, \forall\ t\epsilon T \quad (17)$$

Equation (17) ensures that at each time point the adaptive capacity of the CP is adequate. If the CP has already reached its full capacity, the model should install another cache to serve the remaining traffic of the TP. Calculating the amount of adaptive power transmission of CP *c* if it has a connection with any test point ($\alpha_{ct} = 1$):

$$P\_CP_{TX\_Min\_ct} \leq \ P\_CP_{TXct} \leq P\_CP_{TX\_Max\_ct} \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (18)$$

$$P\_CP_{TX\_ADP\_ct} \leq P\_CP_{TX\_Max\_ct} \times \alpha_{ct} \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (19)$$

$$P\_CP_{TX\_ADP\_ct} \leq P\_CP_{TXct} \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (20)$$

$$P\_CP_{TX\_ADP\_ct} \geq P\_CP_{TXct} - P\_CP_{TX\_Max\_ct} \times (1 - \alpha_{ct}) \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (21)$$

$$P\_CP_{TX\_ADP\_ct} \geq 0 \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (22)$$

Equations (18-22) are used to remove the non-linearity of multiplying two variables ($P\_CP_{TX\_ADP\_ct} = \ P\_CP_{TXct} \ \times \alpha_{ct}$) with linear equations.

$$P\_CP_{TXct} + \ P\_CP_{min\_OPct} - P_{REct} = 0 \quad \forall c\epsilon CP, \forall\ t\epsilon T \quad (23)$$

Equation (23) ensures that the amount of non-renewable energy consumption by CP *c* is equal to zero.

VI. CDN HEURISTIC

A CDN heuristic to validate four different cases of the proposed models has been developed and presented in Algorithm A. These cases are: 1) renewable energy with non-adaptive CPs, 2) renewable energy with adaptive capacity CPs. The traffic (demand) at each CP is already calculated, and the number of the CPs is optimized. The heuristic begins by checking available renewable energy and available number of simultaneous connections (downloads) by lines: 3-5 of Algorithm. For Renewable Energy Non-adaptive case (*RE + NonADP-CPs*) if the number of available connection is lower than that of the requests, rest of traffic demands would drop, as given in lines: 6-12. Renewable energy adaptive case (RE + ADPCPs) is beginning with comparing available wind energy as well as given by line: 14-16. If computed number of simultaneous connection is enough, all traffic would be served by current CPs. If number of connections is more than available connection, required number of CPs would be turned on to serve whole traffic demand, as given by lines: 17-25.

VII. Performance Evaluation

From the results obtained by the MILP models and the heuristic for the CDN, we found the optimal number of CPs to minimise the total network energy consumption traffic demand. According to the available renewable energy and data Figure 4 shows the total energy consumption of the CPs for the proposed models. The result follows the same trend as the hourly vehicular flow Figure 2. The higher vehicular traffic flow during peak hours require higher total energy consumption of the CPs. In the case of renewable energy with non-adaptive CPs (*RE+NonADP-CPs*), all CPs get deactivated at the time periods when wind energy available is less than the total energy required by the CPs. Further, it is observed that due to the lower capacity of the CPs in case of adaptive CPs, there would be an increase in the number of active CPs for serving traffic demand with the maximum download rate. Hence, the power consumption would be higher compared to the other models.

Figure 5 shows the number of simultaneous downloads by a CP in different cases. According to the availability of wind energy, the CPs adjust the serving capacity. In case of NRE, the CPs utilize maximum number of simultaneous downloads due to the availability of sufficient wind energy. The figure illustrates that for the *RE+NonADP-CPs*, number of simultaneous downloads is equal to zero due to inadequate renewable energy in some hours.

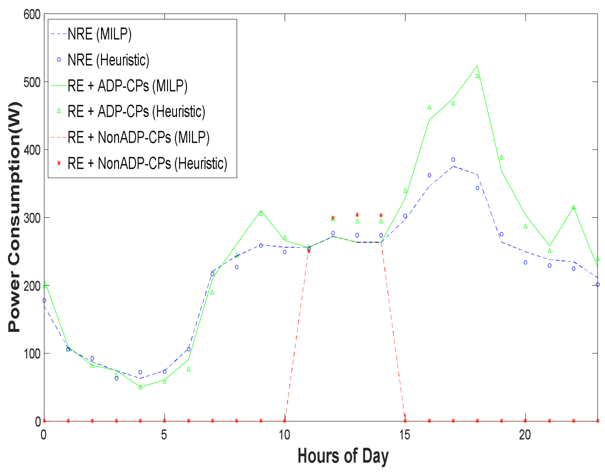

Figure 4 : Total network energy consumption.

Figure 6 shows the total number of active CPs in the network (obtained by respective models) every hour of the day. The number of CPs needed to serve the content demand varies during the day. The number of active CPs is found to be directly proportional to the traffic demand. The results show that for the non-renewable model without energy savings (NRE), the number of CPs activated remains fixed during the lean traffic hours (00:00 – 06:00) as at least 12 CPs serve the demand. Whilst the traffic demand (after 06:00) increases, the number of CPs increase as well. In case of renewable sources with non-adaptive CPs, a deficit of available renewable energy results in the

Algorithm A: CDN heuristic

Input: $Lambda$, *MaxNoOfConnections*, $AvailableWindEnergy$, $RequestedEnergy$

Output: $Number\ of\ CPs\ which\ need\ to\ replace$

```
1.  for all t_1 = 1,2,3,...T_Sim do
2.    for all CPs do
3.      RE with Non Adaptive CPs CASE:
4.      if RequestedEnergy(c) ≤ AvailableWindEnergy(c) then
5.          calculate MaxNoOfConnection
6.          if NeededNoOfConnections ≤ MaxNoOfConnections
7.            Serve traffic demand
8.          end if
9.      else
10.         Turn Off CP
11.         Drop all the requests at CP
12.     end if
13.     end CASE
14.     RE with Adaptive CPs CASE:
15.     if RequestedEnergy(c) ≤ AvailableWindEnergy(c) then
16.         calculate MaxNoOfConnections
17.         if NeededNoOfConnections ≤ MaxNoOfConnections
18.           Serve traffic demand
19.         end if
20.     else
21.         Turn On another CP
22.         calculate MaxNoOfConnections
23.         if NeededNoOfConnections ≤ MaxNoOfConnections
24.           Serve traffic demand
25.         end if
26.     end if
27.   end CASE
28.     compute Delay
29.   end for
30.   t_1++
31. end for
```

average number of active CPs to be zero. Figure 6 shows that the model with all renewable sources and adaptive capacity CPs requires switching ON of additional CPs during a shortage of renewable energy, even if the CPs serve at maximum download rate.

Figure 7 illustrates the total energy saving of each model in comparison with the initial model (*NRE-all CPs ON*). The figure reveals that with Non Adaptive CPs powered by renewable energy, 100% savings can be achieved only during some hours of the day. In other hours, the energy saving by using renewable energy is zero as the traffic cannot be served with renewable energy alone. In the case of *NRE* with energy saving, a sharp peak is observed at 4:00 am, which is due to the lowest number of active CPs required at that time, reflecting least vehicular traffic.

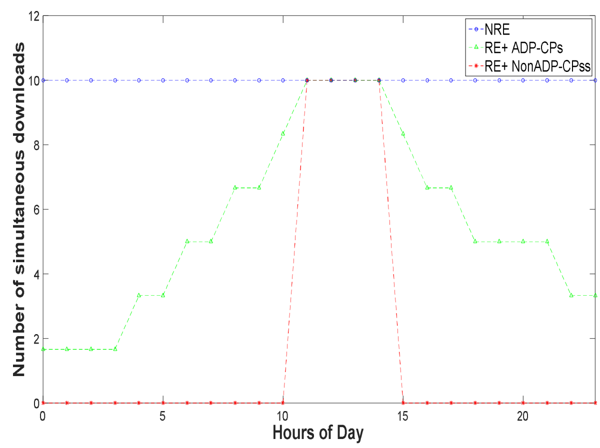

Figure 5: Number of simultaneous downloads.

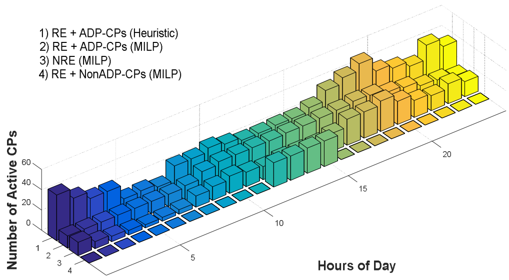

Figure 6 : The number of active caching points.

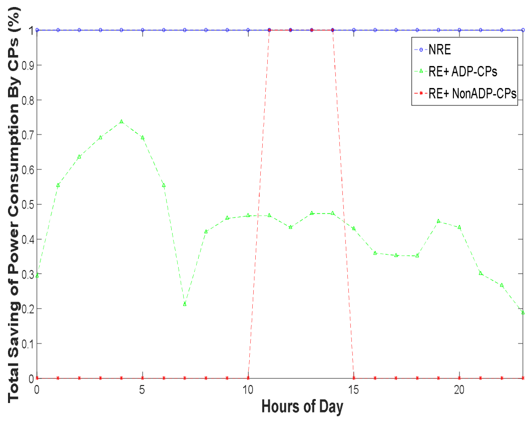

Figure 7 : Total energy saving.

Figure 8 shows average piece delay in *NRE*, *RE+NonAPD-CPs*, *RE+ ADP-CPs*. In the case of *RE+ ADP-CPs*, the average piece delay is higher. However, all energy consumption is renewable energy as the model try to serve the remaining traffic demand due to the capacity (adaptive) bounds on active CPs. In the case of *RE+NonADP-CPs*, the system could only serve 4 hours; hence the respective delay is calculated. The figure shows the inability of *RE+NonADP-CPs* in powering up the CPs required to serve all traffic demand.

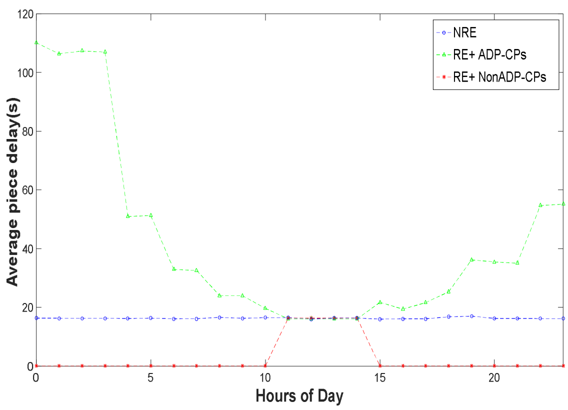

Figure 8: Average piece delay.

VIII. CONCLUSION

In this paper, energy adaptive CPs for vehicular CDN are proposed. The average piece delay at the proposed CPs were dependent on available renewable energy. For non-adaptive CPs, whole traffic demands can only be served at the expense of higher number of active CPs. It means that if we want to keep the same number of CPs, the whole traffic demand won't be served at plenty of hours. This increases the overall average piece delay at earlier hour of the day when available wind energy is insufficient. In contrast, the non-renewable energy consumption increases at lower renewable energy due to the number of active CPs. The advantage of the proposed adaptation capacity technique at a CP operating only with renewable energy is evident in terms of acceptable average piece delay and highest non-renewable energy savings compared to that of a traditional CP. The performance results revealed that the proposed CP saved 100% non-renewable grid energy during the whole day while fulfilling content demand in a city vehicular environment.

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