Design Green Hybrid Fiber-Coaxial Networks: A Traffic-Aware and Cooperative Approach

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***Abstract*—We propose a traffic-aware and cooperative approach to achieve energy-saving in Hybrid Fiber-Coaxial (HFC) networks that support DOCSIS 3.0 standard. The approach incorporates a two-step operation that consists of two algorithms, one for the Cable Modem (CM) side and the other for the Cable Modem Termination System (CMTS) side. To avoid transition overheads, we design both algorithms with the consideration of energy-to-NoC (Number of Changes) tradeoff and try to minimize the number of Dynamic Bonding Change (DBC) operations while saving the energy. Simulations verify the effectiveness of the algorithms by using a realistic HFC network traffic model, and the results demonstrate significant saving on the ON-time (energy consumption) of the CMs' channels and the CMTS' ports.**

***Index Terms*—Hybrid Fiber-Coaxial (HFC) Networks, DOCSIS 3.0, Traffic-aware design, Energy-efficient networks**

I. Introduction

While the remarkable growth of Internet traffic has spurred rapid upgrades of network infrastructures, energy-efficiency becomes a major concern for maintaining the sustainability of network systems. It is estimated that 37% carbon emission of the Information and Communication Technology (ICT) is due to operating the telecommunication infrastructure and equipments [1], and metro/access networks consume more than 60% of the overall energy consumption of communication networks [2]. Consequently, designing green technologies for various access networks has attracted intensive research activities. In [3], the energy efficiency of mobile access networks (e.g. 3G and 4G systems) has been improved by using smart transmission technologies with MIMO and a smaller cell size. Energy efficient and low-power designs within all layers of the wireless network protocol stack have been summarized in [4]. Green digital subscriber line (DSL) technology has been demonstrated in [5] with dynamic spectrum management. By incorporating sleep mode, green network designs have been obtained for passive optical networks (PON) [6], and hybrid wireless-optical broadband access networks (WOBAN) [7]. Hybrid fiber coaxial (HFC) networks can support broadband Internet access over existing Cable TV (CATV) systems. While this technology has the second biggest user population among all wired access networking technologies, the research on improving its energy efficiency is still under-explored.

Data over Cable Service Interface Specification (DOCSIS) is an international industry standard for developing the network equipments of HFC infrastructure [8]. DOCSIS standard defines two primary components in a HFC network: Cable Modems (CM) located at the customer premises, and a Cable Modem Termination System (CMTS) at the cable operator's network head-end. DOCSIS 3.0 standard [8] has been released in 2006, which provides cable operators a remarkable opportunity to outpace competitors such as FTTH providers with immediate implementation of ultra-broadband services at minimal costs. As shown in Fig. 1, the customer number of HFC consistently increased faster than that of FTTH during the last decade. While the new technologies in DOCSIS 3.0 boost up network throughput effectively, they also lead to energy consumption increase. Recently, we have reported a traffic-aware approach to reduce power consumption in DOCSIS 3.0 networks by putting unused network elements into sleep mode [9]. The CM-side results demonstrated effective energy saving, and the energy-to-delay tradeoff had been investigated for system optimization. However, further research is still necessary to explore the CMTS-side algorithm and to evaluate the whole cooperative approach in-depth. Recent experimental evaluation on Energy Efficient Ethernet (IEEE 802.3az) has shown that switching network devices between active and sleep modes too frequently could result in significant transition overheads, and lead to high energy consumption even at low traffic load [10]. Therefore, in addition to the famous energy-to-delay tradeoff, we have to consider the energy-to-NoC (Number of Changes) tradeoff. In this paper, we present a traffic-aware and cooperative approach for designing energy-efficient HFC networks. The energy-saving algorithms are redesigned with the consideration of energy-to-NoC tradeoff, and both CM-side and CMTS-side results are presented to show effective network-wide energy saving.

The rest of the paper is organized as follows. Section II introduces the HFC network infrastructure and the DOCSIS 3.0 standard. Sections III and IV discuss the CM-side and CMTS-side energy-saving algorithms and their optimization procedures, respectively. Finally, Section V summarizes this paper.

II. Hybrid Fiber-Coaxial Networks

A. HFC Network Infrastructure

In HFC networks, a data transmission speed of up to 30 Mbps can be achieved on one RF TV channel (6 or 8 MHz bandwidth) using QAM modulation techniques. Digital signals from a CMTS are distributed through optical fibers organized in a tree hierarchy to optical nodes, where they are converted

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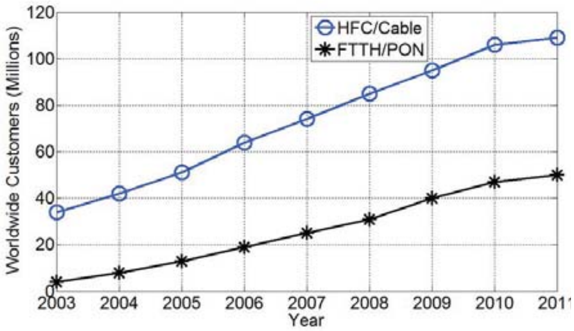

Fig. 1. Worldwide customers using HFC and FTTH technologies.

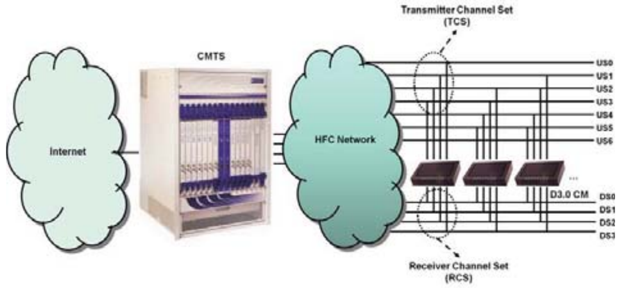

Fig. 2. HFC network supporting DOCSIS 3.0.

into electrical formats and sent to the CMs at subscribers' home using coax cables [8,11]. Both the downstream (DS) and upstream (US) channels in HFC networks are shared by the subscribers in a time-division multiplexing (TDM) manner.

B. DOCSIS 3.0 Standard

DOCSIS 3.0 standard includes several major enhancements to improve the service platform and operating efficiency of networks, such as channel bonding, advanced security and etc. Channel bonding allows multiple RF channels to be grouped into a virtual wideband channel that utilizes the combined bandwidth to achieve over 100 Mbps speed for both US and DS transmissions. The number of bonded channels in both the US and DS directions is usually four.

Fig. 2 illustrates the architecture of a typical HFC network supporting DOCSIS 3.0. The wideband CMs are built with multiple transceivers, and can tune to multiple US/DS ports from the CMTS simultaneously. The CMTS groups its US and DS ports into MAC domains that usually contain at least 8 US and 8 DS ports. The set of US/DS channels that a CM is tuned to is defined as its transmitter channel set (TCS)/receiver channel set (RCS). In most of current implementations of DOCSIS 3.0, the size of a CM's TCS/RCS equals to the number of its transceivers. CMTS determines the size of TCS/RCS at the time of CM registration and usually does not change it afterwards. Hence, the network is dimensioned for peak traffic load. Nevertheless, due to the daily life pattern of end users, the traffic in a HFC network can have relatively large hourly fluctuations [11]. This fact suggests that some of the CMs' transceivers and even CMTS ports can be greatly under-utilized during low-traffic hours.

C. Dynamic Bonding Change and Energy-Saving

DOCSIS 3.0 standard defines a MAC-layer operation, dynamic bonding change (DBC), to adjust the TCS/RCS of a CM without introducing significant traffic disruption [8]. Specifically, CMTS can use DBC to add, delete, or replace US and DS channels in CM's TCS and RCS in one MAC operation. Our proposed energy-saving algorithms use DBC to selectively shut down unused channels. The power consumption PW of a CM usually follows the expression of:

$$PW \propto |TCS| + |RCS| \tag{1}$$

where $|TCS|$ and $|RCS|$ are the numbers of active channels in the CM's TCS and RCS. To achieve network-wide energy saving, the proposed algorithms incorporate a two-step coordinated operation, one for the CM-side and the other for the CMTS-side.

III. CM-Side Energy-Saving

A. Basic Algorithm

The CM-side algorithm defines three operation modes for each transmission direction: 1) high-power mode with N_H US or DS channels, 2) moderate-power mode as N_M channels, and 3) low-power mode as N_L channels. The CMTS maintains two traffic-load thresholds for the CMs, high-watermark (HW) and low-watermark (LW). With a fixed time interval Δt (a few minutes), the CMTS samples the current DS and US traffic loads of the CMs, by measuring the length of corresponding DS input queues and by calculating pending US requests, respectively. The notation of $X_{i,j,m}$ is used for these traffic sampling results, where i is the sampling sequence number, j is for traffic direction (0 for US, and 1 for DS), and m is the CM's ID. This traffic sample $X_{i,j,m}$ can be directly used to determine proper operation mode of a CM. However, due to the fact that the traffic can be highly dynamic, this scheme may turn on and off the channels of a CM too frequently. And the frequent changes can increase dynamic power consumption due to the transition overheads [10], and make network management more complicated. To avoid this side-effect, we introduce another variable $Y_{i,j,m}$ as the traffic load prediction for the next sampling period:

$$Y_{i,j,m} = \sum_{k=0}^{N-1} \lambda_{k,j} X_{i-k,j,m} \tag{2}$$

where $\Lambda_j = \{\lambda_{0,j}, \lambda_{0,j}, .., \lambda_{N-1,j}\}$ are the weighting coefficients for the linear prediction, and N is the number of previous traffic samples for prediction. We then use $Z_{i,j,m}$, the larger value of $X_{i,j,m}$ and $Y_{i,j,m}$:

$$Z_{i,j,m} = \max(X_{i,j,m}, Y_{i,j,m}) \tag{3}$$

as the decision variable. Due to the asymmetry of DS and US traffic, the DS and US channels will be treated separately with the same logic as shown in *Algorithm 1*.

Algorithm 1 CM-Side Energy-Saving Algorithm

Input: Λ_j, HW, LW, Δt
Output: Operation modes of CMs

```
while Energy-saving feature is ON do
    for all CMs in the MAC-domain do
        sample X_{i,j,m};
        calculate Y_{i,j,m} and Z_{i,j,m};
        if Z_{i,j,m} ≥ HW then
            put CM to high-power mode;
        else if Z_{i,j,m} ∈ [LW, HW) then
            put CM to moderate-power mode;
        else
            put CM to low-power mode;
        end if
    end for
    wait for Δt;
end while
```

B. Multi-Objective Optimization with Simulated Annealing

We define the sets of US and DS ports from the CMTS in a MAC domain as

$$USS = \{us_1, us_2, ..., us_M\}, |USS| = M \tag{4}$$

and

$$DSS = \{ds_1, ds_2, ..., ds_K\}, |DSS| = K \tag{5}$$

Then, a CM's TCS and RCS at sampling time i are

$$TCS_{i,m} \in USS, |TCS_{i,m}| \leq T_m \tag{6}$$

$$RCS_{i,m} \in DSS, |RCS_{i,m}| \leq T_m \tag{7}$$

where T_m is the number of transceivers equipped for the CM. It can be seen that the performance of the energy-saving algorithm depends on the choices of *LW*, *HW*, and $\lambda_{k,j}$. While *LW* and *HW* can be found by simply applying the ratios of N_M and N_L to T_m, we use a multi-objective optimization method with modified simulated annealing [12] to find $\lambda_{k,j}$ that can minimize the fitness function $F(\Lambda_j)$:

$$F(\Lambda_j) = (f_1(\Lambda_j), f_2(\Lambda_j)), \Lambda_j = \{\lambda_{0,j}, \lambda_{0,j}, .., \lambda_{N-1,j}\} \tag{8}$$

Here, $F(\Lambda_j)$ involves two objective functions. Function $f_1(\Lambda_j)$ is the summation of the product of hold time and channel set size (Number of Channels $\times$ Hours):

$$f_1(\Lambda_j) = \{ \begin{array}{l} \sum_m \sum_i |TCS_{i,m}|\Delta t, j = 0 \\ \sum_m \sum_i |RCS_{i,m}|\Delta t, j = 1 \end{array} \tag{9}$$

According to Eqn. (1), this function reflects the energy consumption of the CMs' channels:

$$f_1(\Lambda_j) \propto \sum_m E^{CM}_{j,m} \tag{10}$$

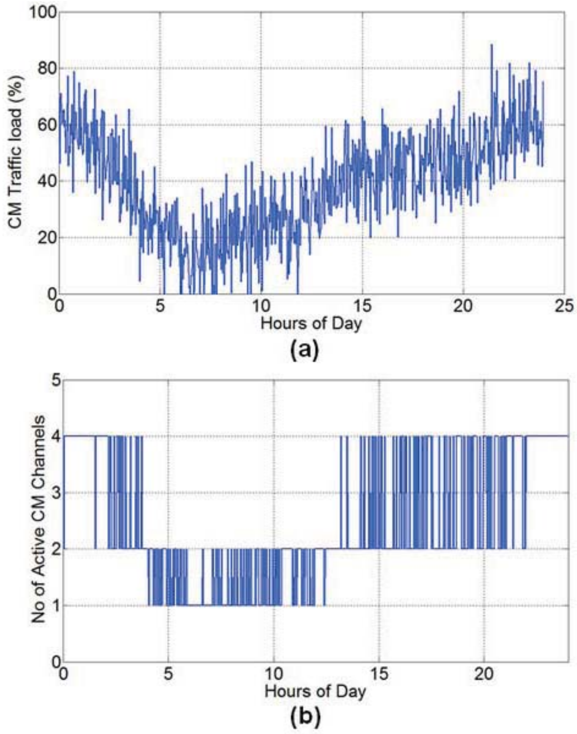

Fig. 3. (a) CM DS traffic load variation, (b) Number of a CM's active DS channels in a 24-hour period when using optimized $\lambda_{k,1}$.

Function $f_2(\Lambda_j)$ is the number of total DBC operations, reflecting NoC. We say $F^1 = F(\Lambda_j)$ dominates $F^2 = F(\Lambda'_j)$, if $f_1(\Lambda_j) < f_1(\Lambda'_j)$ and $f_2(\Lambda_j) < f_2(\Lambda'_j)$. The optimization procedure tries to balance the trade-off between $f_1(\Lambda_j)$ and $f_2(\Lambda_j)$.

C. Simulation Results

The parameters of the simulations are listed in Table I. For simplicity, we only simulated DS direction operation. Each CM has independent self-similar traffic input [11], which follows a similar overall trend as shown in Fig. 3(a). Table II shows the comparisons of $f_1(\Lambda_j)$ and $f_2(\Lambda_j)$ for four scenarios: 1) Normal case without any DBC changes, 2) No prediction case as $\lambda_{k,1} = 0, k = 0, ..., N-2; \lambda_{N-1,1} = 1$, 3) Average prediction case as $\Lambda_j = \{\lambda_{k,j} = \frac{1}{N}\}, k = 0, 1, ..., N-1$, and 4) Optimized prediction case with Λ_j from the multi-objective optimization. The results show that the optimized prediction case achieves 38.37% saving on $f_1(\Lambda_j)$ (energy consumption), compared to the normal case, and 31.72% saving on $f_2(\Lambda_j)$ (NoC) compared to the no prediction case. Fig. 3(b) shows how the number of a CM's active DS channels changes with the traffic load when using the optimized prediction case.

IV. CMTS-Side Energy-Saving

A. Mathematical Formulation

The CMTS-side algorithm works as the second phase of the cooperative energy-saving, in which we find the actual

TABLE I
SIMULATION PARAMETERS

T_m, number of a CM's transceivers	4
N_H, number of high-power mode channels	4
N_M, number of moderate-power mode channels	2
N_L, number of low-power mode channels	1
HW, high-watermark traffic threshold in load	50%
LW, low-watermark traffic threshold in load	25%
Total number of CMs	32
Δt, traffic sampling interval	2 Minutes
N, size of Λ_1	5
K, number of DS ports in the CMTS's MAC domain	16
Total simulation duration for CM operation	24 Hours
Number of simulations for statistical accuracy	128

TABLE II
COMPARISONS OF CM-SIDE SIMULATION RESULTS

	Normal Case	No Prediction Case	Average Prediction Case	Optimized Prediction Case
$f_1(\Lambda_1)$	3072	1773	1915.3	1893.2
$f_2(\Lambda_1)$	0	9189	5864	6274

connection mapping between CMs' channels and CMTS' ports. We then count the number of CMs connected to a CMTS port, and shut down idle or under-utilized ports for energy-saving on the CMTS-side. With the definitions of input parameters and variables in Table III, we formulate an integer linear problem (ILP):

Minimize:

$$\sum_i \sum_k US_{i,k} + \sum_i \sum_k DS_{i,k} \tag{11}$$

Subject to:
Connection Constraints:

$$\sum_k L_{i,0,m,k} = P_{i,m} \tag{12}$$

$$\sum_k L_{i,1,m,k} = Q_{i,m} \tag{13}$$

Capacity Constraints:

$$\sum_m L_{i,0,m,k} \leq U \tag{14}$$

$$\sum_m L_{i,1,m,k} \leq D \tag{15}$$

Operation Complexity Constraint:

$$\sum_m DBC_m \leq DBC_{max} \tag{16}$$

With this ILP formulation, we can obtain the optimized connection mapping between CMs and CMTS for each sampling point i. However, since the energy-saving algorithm is running on a real-time CMTS system with thousands of CMs, computation resource and time will become a concern when implementing this ILP based solution. With this consideration in mind, we propose a heuristic algorithm for CMTS-side energy-saving, by greedily grouping CM connections with the minimal number of CMTS ports.

TABLE III
INPUT PARAMETERS AND VARIABLES FOR CMTS-SIDE ALGORITHM

$US_{i,k}/DS_{i,k}$	Status of CMTS's k-th US/DS port at sampling time i. The value is 0 for shut-down or sleep mode, and 1 for active.
U/D	Capacity of a CMTS's US/DS port as the number of connected CMs
$P_{i,m}$ / $Q_{i,m}$	Number of active US/DS channels on CM m at sampling time i, calculated by *Algorithm 1*
$L_{i,0,m,k}$ / $L_{i,1,m,k}$	The value is 1, if CM m connects to the k-th US/DS port from the CMTS at sampling time i; and is 0, otherwise.
DBC_m	Total number of DBC changes for CM m.
DBC_{max}	Maximum number of total DBC changes we can accommodate.

B. Heuristic Algorithm

Similar to the CM-side operations, the US and DS directions can be handled separately. We define a load threshold TH for CMTS ports. *Algorithm 2* illustrates the heuristic algorithm for CMTS-side energy-saving. The proposed algorithm consists of two phases. In Phase-I, we obtain the desired sizes of TCS/RCS of CMs with *Algorithm 1*, direct new CM connections to the available CMTS ports that are busiest, and take off CM connections from the lightest ports. In Phase-II, we readjust the connection mapping between CMs and CMTS based on *TH*, and the connections on CMTS ports with loads below *TH* are redistributed to busier ones with DBC until no change can be made.

C. Simulation Results

Using the parameters in Table I, we simulate a CMTS system with 1000 CMs. The DS port capacity is set as $D = 256$ to accommodate 90% load, reserving 10% load as the performance margin. The coefficients $\lambda_{k,1}$ of the CMs are obtained with the simulated annealing optimization in Section III.C. Fig. 4 shows the number of active CMTS ports changing with time for $TH = 0.1D$. Fig. 5 shows the trade-off between CMTS energy-saving and additional NoC from the CM-CMTS connection readjustment (*Algorithm 2* Phase-II). One hundred network-wide simulations have been performed with different values of $TH \in [0, 0.2D]$. The comparisons of ON-time (energy consumption) of CMTS ports in a 24-hour period are plotted in Fig. 6 for three scenarios. Each plot in Fig. 6 is obtained by averaging the results of 32 simulations.

V. CONCLUSIONS

We proposed a traffic-aware and cooperative approach to achieve energy-saving in HFC networks that support the DOCSIS 3.0 standard. The approach incorporated a two-step operation that consisted of two algorithms, one for the CM-side and the other for the CMTS-side. Both algorithms were designed with the consideration of energy-to-NoC tradeoff. We then verified the effectiveness of the algorithms with simulations using a realistic HFC network traffic model. The simulation results demonstrated over 38% saving on the ON-time (energy consumption) of the CMs' channels, and over

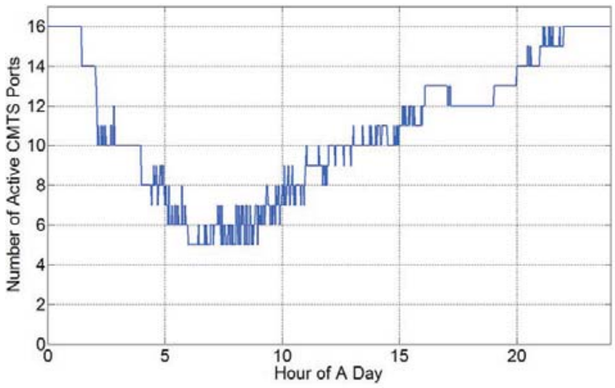

Fig. 4. Number of active CMTS ports changing with time for $TH = 0.1D$.

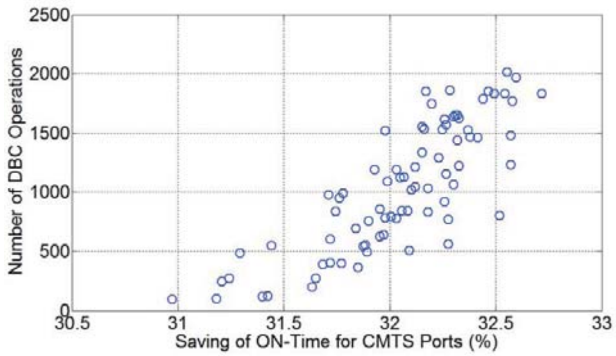

Fig. 5. Number of additional DBC operations from the readjustment phase vs. Saving of ON-time for CMTS ports.

31.5% saving on the ON-time of the CMTS' ports. Hence, network-wide energy saving had been obtained, for lowering operational cost (OPEX) and reducing environmental impacts.

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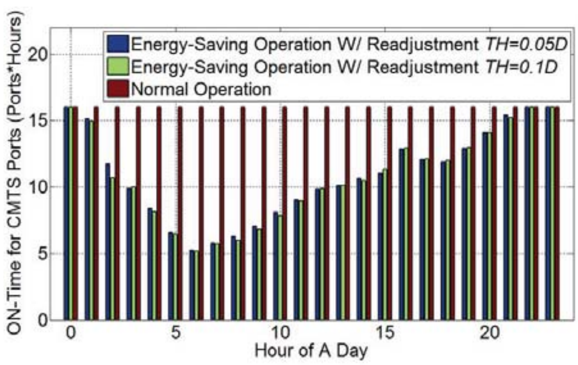

Fig. 6. Comparisons of ON-time for CMTS ports.

Algorithm 2 CMTS-Side Energy-Saving Algorithm

Input: $\{P_{i,m}\}/\{Q_{i,m}\}$, TH

Output: Operation modes of CMTS's US/DS ports

```
{Phase I}
for all CMs in the MAC-domain do
    if (P_{i,m} > P_{i-1,m})/(Q_{i,m} > Q_{i-1,m}) then
        add (P_{i,m} - P_{i-1,m})/(Q_{i,m} - Q_{i-1,m}) connections
        to the busiest CMTS US/DS ports with DBC;
        sort all CMTS US/DS ports;
    else if (P_{i,m} < P_{i-1,m})/(Q_{i,m} < Q_{i-1,m}) then
        delete (P_{i-1,m} - P_{i,m})/(Q_{i-1,m} - Q_{i,m}) connections
        from the lightest CMTS US/DS ports with DBC;
        sort all CMTS US/DS ports;
    end if
end for
{Phase II}
for CMTS US/DS ports from lightest to busiest do
    if (\sum_m L_{i,0,m,k} > TH)/(\sum_m L_{i,1,m,k} > TH) then
        break;
    end if
    redistribute US/DS connections on the port to busier
    ones with DBC;
    if (\sum_m L_{i,0,m,k} = 0)/(\sum_m L_{i,1,m,k} = 0) then
        shut down the port;
    end if
    sort all CMTS US/DS ports;
end for
```

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