Design of Energy-Saving Algorithms for Hybrid Fiber Coaxial Networks Based on the DOCSIS 3.0 Standard

Zuqing Zhu

***Abstract*—We propose energy-saving algorithms to improve the energy efficiency of hybrid fiber coaxial (HFC) networks that support DOCSIS (Data Over Cable Service Interface Specification) 3.0 standard. The algorithms incorporate a traffic-aware approach and modify the operation statuses of the two primary network elements, the cable modem (CM) and the cable modem termination system (CMTS), dynamically. For the CM-side operation, we first propose a basic algorithm that can optimize the CMs' energy efficiency, regardless of significant increase of the packet delay and the number of operation changes (NoOC). We then propose two modified approaches to reduce the packet delay and NoOC while saving energy. Simulations with these algorithms show 37.5%–42.2% energy saving on the CM side, compared to the traditional case where the CMs' operation statuses are static. Next, we propose a CMTS-side energy-saving algorithm to find the actual connection mapping between the CM channels and CMTS ports. The proposed algorithm tries to support CM connections with minimal numbers of CMTS ports. To further improve the energy efficiency of the CMTS, we design a readjustment approach that can reorganize CM connections on CMTS ports based on their loads. Simulation results show that 31.08%–32.61% energy saving can be achieved on the CMTS in total. Hence, the proposed algorithms achieve effective energy saving on both the CM and CMTS sides.**

***Index Terms*—DOCSIS 3.0; Energy-efficient networks; Hybrid fiber coaxial (HFC) networks; Multi-objective optimization; Traffic-aware design.**

I. Introduction

Due to the exponential growth of Internet traffic, both the equipment and the infrastructure of communication networks have been upgraded rapidly in the last decade. The consequent increase in power consumption has raised concerns on the operational cost (OPEX) and environmental impact of information and communication technology (ICT). It is estimated that ICT has already contributed to 2%–10% of the carbon emission produced by human activities [1]. Such emissions are expected to increase steadily, especially in access networks [2]. Therefore, energy efficiency has become an attractive research topic for maintaining the sustainability of access network systems, and various green technologies have been proposed [3–8]. In [3], the energy efficiency of mobile access networks (e.g., 3G and 4G systems) was improved by using smart transmission technologies with multiple-input and multiple-output and a small cell size. For wireless local area networks, the research work in [7] proposed an energy-efficient multi-polling mechanism that utilized a power management strategy and a low overhead medium access control (MAC) protocol. Green digital subscriber line (DSL) technology was demonstrated in [4] with dynamic spectrum management. By incorporating sleep modes, energy-efficient network designs have been obtained for Ethernet [8], passive optical networks (PONs) [5], and hybrid wireless optical broadband access networks (WOBANs) [6].

A hybrid fiber coaxial (HFC) network has an infrastructure that combines optical fibers and coaxial cables. It has been employed globally by cable operators to deliver broadband Internet access over existing cable TV (CATV) systems since the early 1990s [9]. While this technology has the second biggest user population among all wired access networking technologies, research on improving its energy efficiency is still underexplored. Data Over Cable Service Interface Specification (DOCSIS) is an international industry standard for developing equipment for HFC networks [10]. Recently, DOCSIS 3.0 [10] was released to enable cable operators to outpace competitors such as FTTx (fiber to the x) providers. DOCSIS 3.0 redefined the communications between the two primary components in an HFC network, i.e., the cable modem (CM) located at the customer premises, and the cable modem termination system (CMTS) at cable operator's network headend. Specifically, multiple upstream (US) or downstream (DS) channels are allowed to be bonded together and work as a virtual channel for high-speed data transmission. This channel bonding technology can push the bi-directional transmission speeds of a CM up to 100 Mbps or more. However, it also increases the power consumption in HFC networks dramatically. The CM has to turn on multiple transceivers to accommodate the bonding requirement, while the CMTS has to equip line cards with an increased number of US/DS ports. Recently, we have reported several traffic-aware approaches to reduce the energy consumption in HFC networks based on DOCSIS 3.0 [11,12]. The algorithms achieved energy saving by putting unused network elements into sleep mode. However, further investigation is still necessary to refine the algorithms and to evaluate the whole cooperative approach in-depth. Moreover, recent research on energy-efficient Ethernet (IEEE 802.3az) has found that switching network devices between active and sleep modes too frequently could result in significant

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The author is with the School of Information Science and Technology, University of Science and Technology of China, Hefei, Anhui 230027, China (e-mail: zqzhu@ieee.org).

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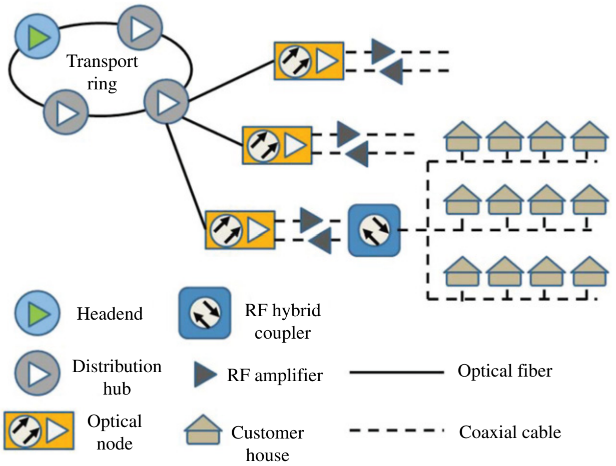

Fig. 1. (Color online) HFC network infrastructure.

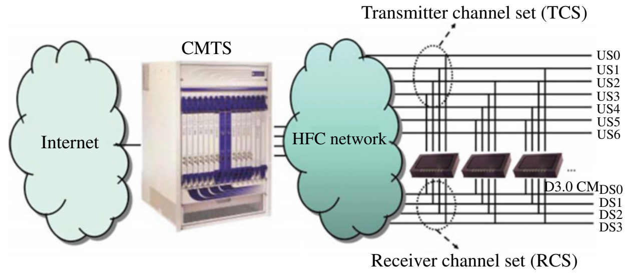

Fig. 2. (Color online) Four-channel bonding in an HFC network with DOCSIS 3.0.

transition overheads and lead to high power consumption even at low traffic load [13]. Therefore, we have to consider how to limit the number of operation changes (NoOC) when designing the energy-saving algorithms.

In this paper, we propose energy-saving algorithms to improve the energy efficiency of HFC networks that support the DOCSIS 3.0 standard. When designing these algorithms, we consider both the tradeoff between energy saving and packet delay and the tradeoff between energy saving and NoOC. The simulation results show effective energy saving on both the CM and CMTS sides, and hence the network-wide energy efficiency can be improved, to enable the cable operators to reduce both the OPEX and the environmental impacts.

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

II. HFC Networks With DOCSIS 3.0

A. Operation Principles of HFC Networks

In HFC networks, cable operators utilize RF TV channels to carry digitally modulated signals for supporting data services. As shown in Fig. 1, digital signals from the operator's headend are distributed through optical fibers to the optical nodes, where they are converted into electrical format and sent to the subscribers using coaxial cables [10,14]. Since there are RF amplifiers in the HFC infrastructure, relatively high access speed can be provided to the subscribers without distance limitation. In an HFC network, the subscribers share both the US and DS channels in a time-division multiplexing manner. In the DS direction, the CMTS packs data to different CMs in different time slots, while US data transmission is achieved by CMs sending requests for future transmission opportunities and the CMTS granting the requests based on a scheduling mechanism.

B. Channel Bonding in the DOCSIS 3.0 Standard

To boost up network throughput, channel bonding in DOCSIS 3.0 groups multiple RF channels into a virtual wideband channel. The number of bonded channels is usually 4 or 8. When the market conditions dictate, operators can migrate to larger bonded channel counts, limited only by the RF spectrum bandwidth in the HFC network. Figure 2 illustrates four-channel bonding in an HFC network with DOCSIS 3.0. In the channel bonding mode, the wideband CM (D3.0 CM) turns on its transceivers, and connects them to multiple US and DS ports on the CMTS simultaneously. The management software on the CMTS groups its physical ports into MAC domains. DOCSIS 3.0 defines the set of US/DS ports that a CM is connected to as its transmitter channel set (TCS)/receiver channel set (RCS).

C. Energy Saving With Dynamic Bonding Change

In most of the current implementations of DOCSIS 3.0, the CMTS determines the sizes of a CM's TCS and RCS in CM registration and does not change them afterward. Hence, the network is dimensioned for peak traffic load statically. Nevertheless, due to the daily life pattern of human beings, the traffic load in an HFC network can have relatively large hourly fluctuations [14]. This fact suggests that both the CMs' transceivers and the CMTS' ports can be greatly underutilized in low traffic hours, such as 4–7 am.

The DOCSIS 3.0 standard defines dynamic bonding change (DBC) as a MAC-layer operation, to adjust the TCS and RCS of a CM without introducing significant traffic disruption [10]. Specifically, with DBC, a CMTS can add, delete, or replace US and DS channels in a CM's TCS and RCS and keep the CM online. Hence, we propose to adjust the operation modes of the network elements (e.g., CMTSs and CMs) in HFC networks dynamically with DBC to save energy. When a port is deactivated, both the dynamic power consumption from data transmission and the static counterpart from powering on the transceivers can be saved. Our proposed algorithms adjust both the CM and CMTS in a coordinated way to reduce the network-wide energy consumption.

TABLE I
SIMULATION PARAMETERS

Number of transceivers in a CM	4
$N^{(\text{High})}$	4
$N^{(\text{Moderate})}$	2
$N^{(\text{Low})}$	1
HW	50%
LW	25%
M, total number of CMs	1024
Δt	2 min
L_{avg}	1518 bytes
$C_{\max}$	30 Mbps
Total simulation duration for CM operation	24 h
Number of simulations for statistical accuracy	128
Energy consumption of an active channel in an hour	1 unit

III. ALGORITHM DESIGN FOR CM-SIDE ENERGY SAVING

A. Basic Algorithm

Since it may not be necessary to turn on all transceivers in a CM all the time, we define three operation modes for the CM: 1) high-power mode with $|S| = N^{(\text{High})}$, 2) moderate-power mode with $|S| = N^{(\text{Moderate})}$, and 3) low-power mode with $|S| = N^{(\text{Low})}$, where S is the CM's channel set. Due to the asymmetry of US and DS traffic, the US and DS channels of a CM need to be handled separately, but with the same logic. Therefore, the algorithms we discuss in the following sections can be applied to an arbitrary transmission direction (i.e., US or DS), and we will not specify US or DS any more. To achieve energy saving, the management software on the CMTS maintains two traffic thresholds, high-watermark (HW) and low-watermark (LW). With a fixed time interval Δt (a few minutes), the CMTS samples the DS and US traffic loads of a CM, by measuring the length of the corresponding DS input queue and by calculating pending US requests, respectively. We use a notation of $X_{i,m}$ for the traffic samples, where i is the sampling sequence number, and m is the CM's unique ID in the CMTS MAC domain.

Algorithm 1 illustrates a basic energy-saving algorithm that uses $X_{i,m}$ as the decision variable, and changes CMs' channel sets accordingly with DBC. To evaluate the performance of this algorithm, we designed simulations with the parameters listed in Table I. Each CM has an independent traffic input that is generated by using a realistic HFC network traffic model with self-similarity [14]. Figure 3(a) shows the traffic load variations of a CM in the simulation, and the traffic of all the other CMs follows a similar overall trend. Based on the traffic variations, *Algorithm* 1 obtains the number of active channels for the CM, as shown in Fig. 3(b). Adopting an M/M/1 queue model, we approximate the packet's queueing delay as

$$D_{i,m} = \frac{L_{\text{avg}}}{C_{\max}} \frac{1}{(|S_{i,m}|/4 - X_{i,m})}, \quad (1)$$

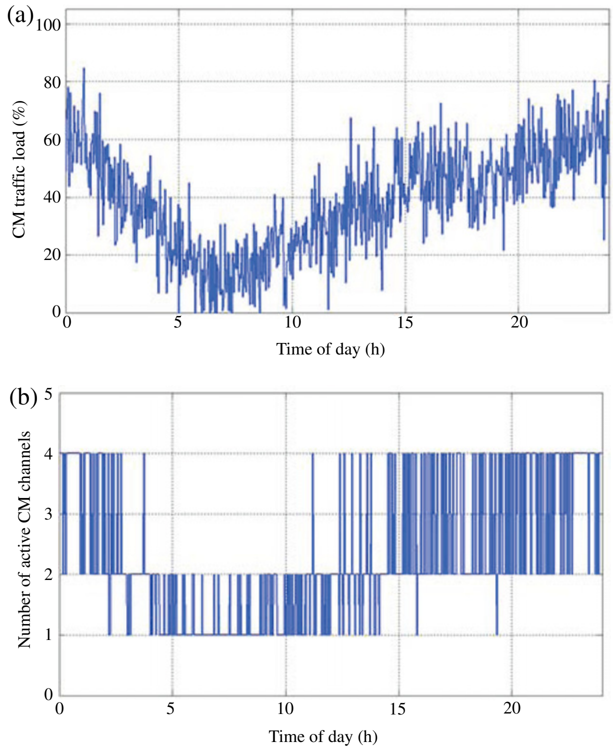

Fig. 3. (Color online) (a) CM traffic load variation in a 24-h period, (b) number of active CM channels from *Algorithm* 1.

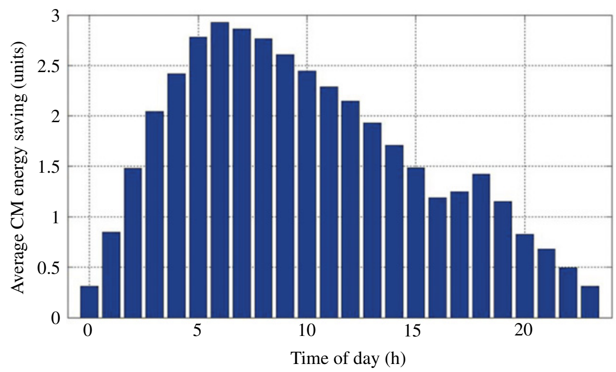

Fig. 4. (Color online) Energy saving per CM hourly for a 24-h duration.

where L_{avg} is the average packet size, $C_{\max}$ is the maximum capacity of one channel, and $S_{i,m}$ is the channel set of CM m at sampling time i. If we assume that the energy consumption of an active channel in an hour is one unit, Fig. 4 shows the hourly energy saving per CM. The simulation results show that *Algorithm* 1 achieves a total energy saving of 40.52 units/CM, compared to the traditional case where the channel sets of CMs will not be dynamically adjusted. The total number of DBC operations per CM is 296. These results are obtained by averaging the data from 128 simulations that each simulate 1024 CMs. Figure 5 shows the per CM values of the packet queueing delay and the number of DBC operations in each hour of a day, respectively.

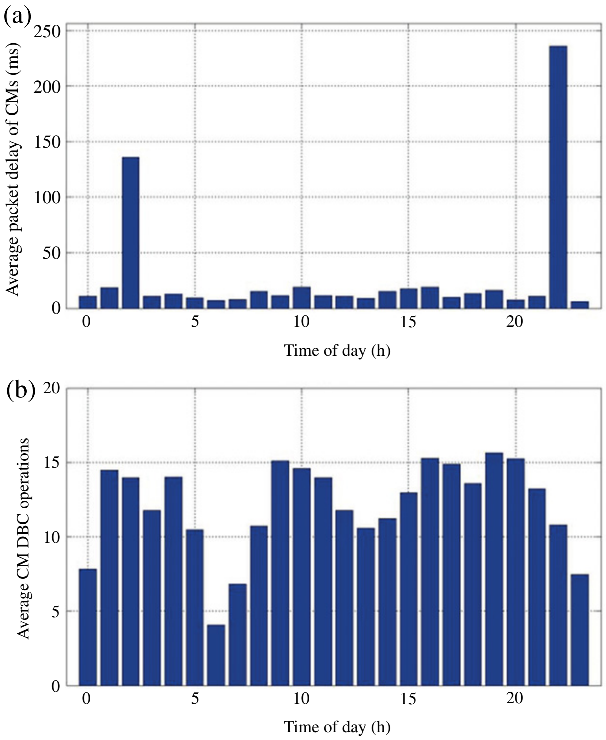

Fig. 5. (Color online) Per CM values of (a) packet queueing delay, and (b) number of DBC operations, in each hour of a day.

Algorithm 1 CM-Side Energy-Saving Algorithm

Input: HW, LW, Δt
Output: Operation modes of CMs in terms of channel sets

```
while energy-saving feature is ON do
    for all CM_m in the MAC domain do
        X_{i,m} = Sample(CM_m, i);
        if X_{i,m} ≥ HW then
            Change_ChannelSet(CM_m, N^(High));
        else if X_{i,m} ∈ [LW, HW) then
            Change_ChannelSet(CM_m, N^(Moderate));
        else
            Change_ChannelSet(CM_m, N^(Low));
        end if
    end for
    Wait(Δt);
end while
```

B. Average Prediction

As shown in Fig. 5, *Algorithm* 1 can introduce too many DBC operations (NoOC) and relatively large packet delay. We modify it by adding the prediction of traffic in the next sampling period, $Y_{i,m}$, as another parameter. If we use an average prediction mechanism

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

where N is the number of previous traffic samples that are used for prediction. We then use $Z_{i,m}$, the larger value of $X_{i,m}$ and $Y_{i,m}$,

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

as the decision variable and modify *Algorithm* 1 accordingly.

Simulations with the same parameters as in Table I are then performed for this average prediction case. We assign N as 5 and 10, and compare the algorithm performance. The simulation results in Table II show that 1) for $N = 5$, the algorithm achieves a total energy saving of 35.97 units/CM, and the number of total DBC operations per CM is 186; 2) for $N = 10$, the results are 35.83 units/CM and 177, respectively. We can see that by sacrificing ~12% energy saving, the average prediction cases can reduce the NoOC by ~40%, and the performance in terms of packet delay is also improved. For a different value of N, the $N = 10$ case achieves better performance in terms of the packet delay and NoOC by sacrificing less than 0.5% energy saving. Figure 6 shows a comparison of the hourly energy saving per CM. Figure 7 shows comparisons of the per CM values of packet delay and number of DBC operations (NoOC), respectively.

C. Multi-objective Optimization With Simulated Annealing

To further explore the tradeoff between energy saving and packet delay and NoOC, we modify Eq. (2) to

$$Y_{i,m} = \sum_{k=0}^{N-1} \lambda_k X_{i-k,m}, \tag{4}$$

where $\Lambda = \{\lambda_0, \ldots, \lambda_{N-1}\}$ is the set of arbitrary weighting coefficients for the linear prediction that

$$\sum_{k=0}^{N-1} \lambda_k = 1, \quad \lambda_k \geq 0. \tag{5}$$

We then define a multi-objective optimization to search for the best values of λ_k, using a modified simulated annealing method [15]. The fitness function is

$$F(\Lambda) = (f_1(\Lambda), f_2(\Lambda)). \tag{6}$$

TABLE II
COMPARISONS OF SIMULATION RESULTS FOR CM ENERGY CONSUMPTION AND NOOC

	Traditional case	No prediction case	Average prediction case ($N = 5$)	Average prediction case ($N = 10$)	Optimized prediction case ($N = 5$)
Energy/CM (units)	96	55.48	60.03	60.17	58.61
Energy saving/CM (units)	0	40.52	35.97	35.83	37.39
NoOC/CM	0	296	186	177	191

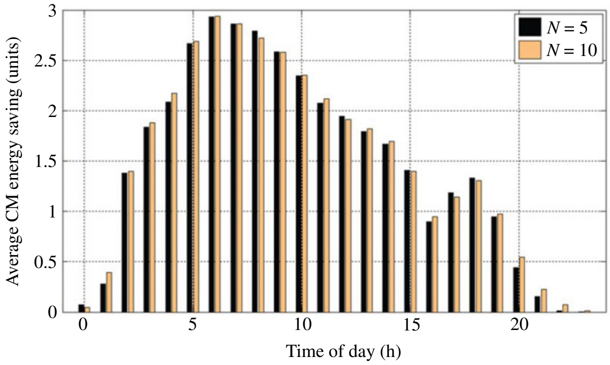

Fig. 6. (Color online) Hourly energy saving per CM in a 24-h duration, for the average prediction cases.

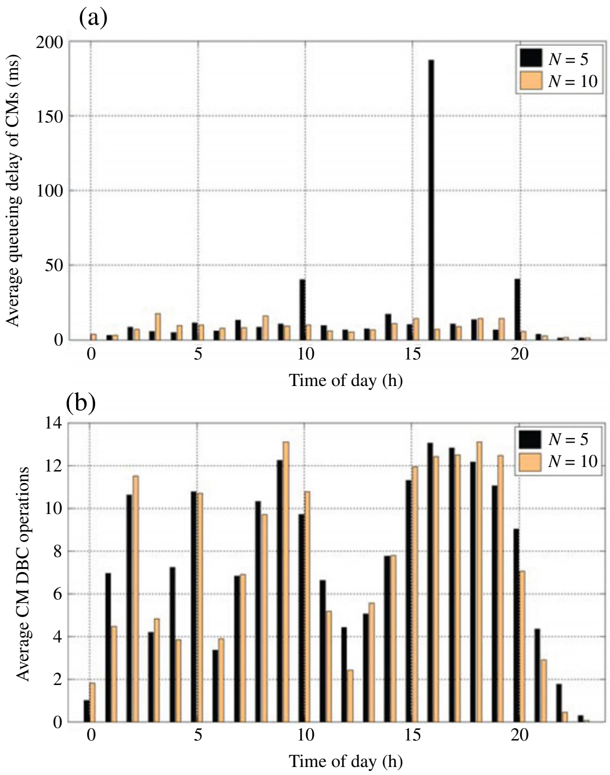

Fig. 7. (Color online) Per CM values of (a) packet queueing delay and (b) number of DBC operations, in each hour of a day, for the average prediction cases.

Here, $f_1(\Lambda)$ is the per CM energy consumption as the summation of the product of channel set size and channel on time (number of channels × hours):

$$f_1(\Lambda) = \frac{1}{M} \sum_m \sum_i |S_{i,m}| \Delta t, \tag{7}$$

where $|S_{i,m}|$ is the size of the CM channel set for CM m at time sequence i, and M is the total number of CMs. $f_2(\Lambda)$ is the per CM NoOC as the average number of DBC operations. The traffic model is the same as that used in Subsections III.A and III.B. In the optimization, we say that $F^1 = F(\Lambda)$ dominates $F^2 = F(\Lambda')$, if $f_1(\Lambda) < f_1(\Lambda')$ and $f_2(\Lambda) < f_2(\Lambda')$. We also define two acceptance probability functions, $P_1(f_1(\Lambda), f_1(\Lambda'), \text{TEMP})$ and $P_2(f_2(\Lambda), f_2(\Lambda'), \text{TEMP})$, and they are calculated when the condition for F^1 dominating F^2 is not satisfied. Here, TEMP is the time-varying temperature for the simulated annealing. The optimization procedures are given in *Algorithm* 2.

Table II shows comparisons of the energy consumption/CM and NoOC/CM for five scenarios: 1) the traditional case without any DBC changes, 2) the no prediction case as in Subsection II.A, 3) the average prediction case as in Subsection II.B with $N = 5$, 4) the average prediction case with $N = 10$, and 5) the optimized prediction case with parameters from the multi-objective optimization ($N = 5$). Since we give preference to energy saving in the multi-objective optimization, the results in Table II show a slightly increased NoOC, and the optimization improves the energy saving from 35.97 to 37.39 units/CM compared to the average prediction.

Algorithm 2 Multi-objective Optimization of Λ with Modified Simulated Annealing

```
Λ = {λ_k = 1/N};
Λ_best = Λ;
run Algorithm 1 for all CMs over a 24-h period with Λ;
calculate f_1(Λ) and f_1(Λ);
TEMP = 1;
while TEMP > TEMP_min do
    modify constant number of λ_k in Λ randomly to get Λ';
    run Algorithm 1 for all CMs over a 24-h period with Λ';
    calculate f_1(Λ') and f_1(Λ');
    if f_1(Λ') < f_1(Λ) and f_2(Λ') < f_2(Λ) then
        Λ_best = Λ';
        Λ = Λ';
    else if f_1(Λ') < f_1(Λ) then
        calculate P_2(f_2(Λ), f_2(Λ'), TEMP);
        if random() < P_2(f_2(Λ), f_2(Λ'), TEMP) then
            Λ = Λ';
        end if
    else if f_2(Λ') < f_2(Λ) then
        calculate P_1(f_1(Λ), f_1(Λ'), TEMP);
        if random() < P_1(f_1(Λ), f_1(Λ'), TEMP) then
            Λ = Λ';
        end if
    else
        calculate P_1(f_1(Λ), f_1(Λ'), TEMP);
        if random() < P_1(f_1(Λ), f_1(Λ'), TEMP) then
            Λ = Λ';
        end if
    end if
    TEMP = 0.8 × TEMP;
end while
```

IV. Algorithm Design for CMTS-Side Energy Saving

A. Basic Algorithm

When the CM-side energy-saving algorithm has determined the size of each CM's channel set at each time sequence i, the

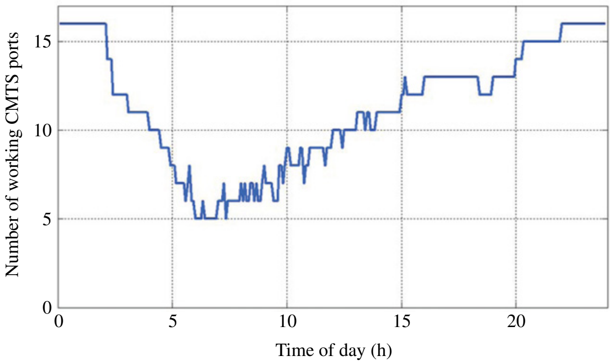

Fig. 8. (Color online) Number of working CMTS ports changing with time.

CMTS-side algorithm kicks in to find the actual connection mapping between the CMs' channels and the CMTS' ports. The idle or underutilized CMTS ports can then be put into sleep mode or shut down for energy saving. We propose a CMTS-side energy-saving algorithm that greedily groups CM connections with minimal numbers of CMTS ports. Specifically, when we need to increase the size of a CM's channel set, we direct the new connections to the busiest CMTS ports, and when we decrease the size of a CM's channel set, we take off connections from the lightest ports.

With the parameters in Table I, we simulate a CMTS system with 1024 CMs. We assume there are 16 CMTS ports in the MAC domain and each can accommodate 256 CM connections for 90% load, reserving 10% load for performance margin. The prediction parameters λ_k are obtained by the multi-objective optimization in Subsection III.C. Figure 8 shows the number of working CMTS ports changing with time. Figure 9 shows the loads (in percentage) of four CMTS ports versus time in a day. Since the proposed algorithm purposely increases the loads of busy ports (e.g., port 1 and port 13 in Figs. 9(a) and 9(c)) and decreases those of light ports (e.g., port 7 and port 15 in Figs. 9(b) and 9(d)), the load distribution is imbalanced. Then, the unused CMTS ports can be put into sleep mode for energy saving.

B. CMTS Readjustment

To further improve the energy saving on the CMTS side, we introduce a CMTS readjustment phase, in which the CMTS readjusts the connection mapping between CMs and itself based on a predefined threshold TH. Specifically, after the CM–CMTS connection mapping is done, the CMTS tries to redistribute connections on ports whose load is below TH to busier ones with DBC, until no change can be made. *Algorithm* 3 shows the details of the CMTS-side energy-saving algorithm with this readjustment.

To evaluate the performance of this readjustment, we perform simulations with the same parameters as in Subsection IV.A and set TH = 0%–20% in terms of the capacity of a CMTS port. Figure 10 compares the number of working CMTS ports for TH = 5% and TH = 20% before and after the readjustment at each time sequence i. It can be seen that the readjustment can usually reduce the number of working CMTS ports by 1 or 2. As expected, the readjustment with a higher TH can put more CMTS ports into sleep mode, with

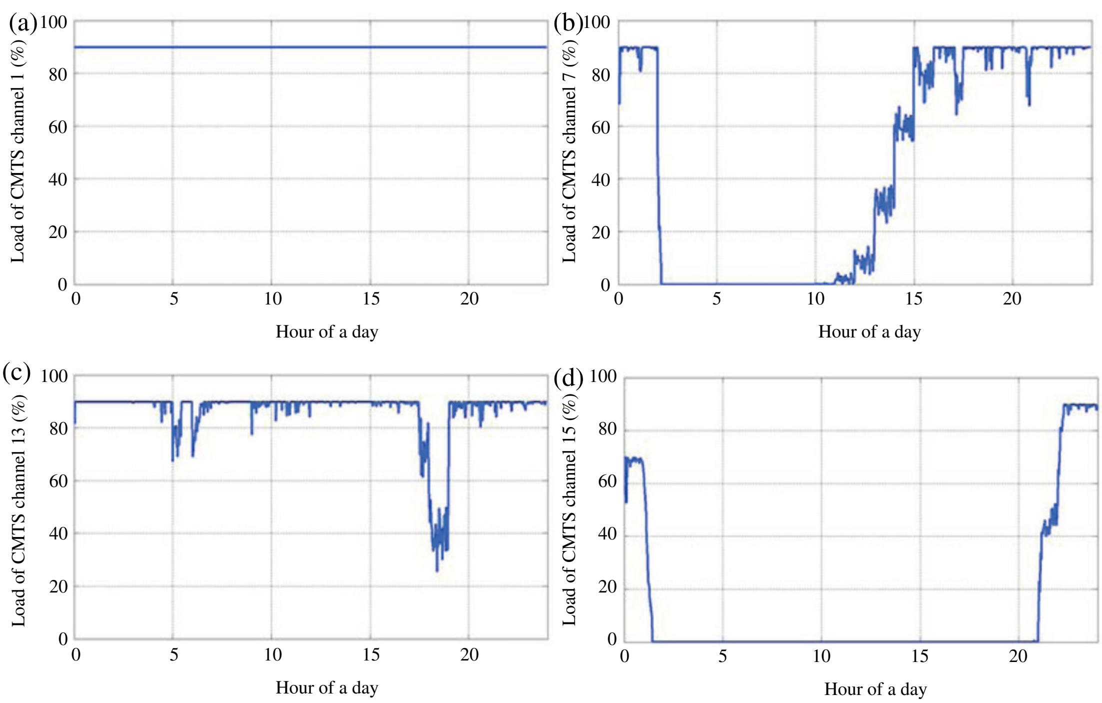

Fig. 9. (Color online) Loads (%) of (a) port 1, (b) port 7, (c) port 13, and (d) port 15 on the CMTS versus time in a day.

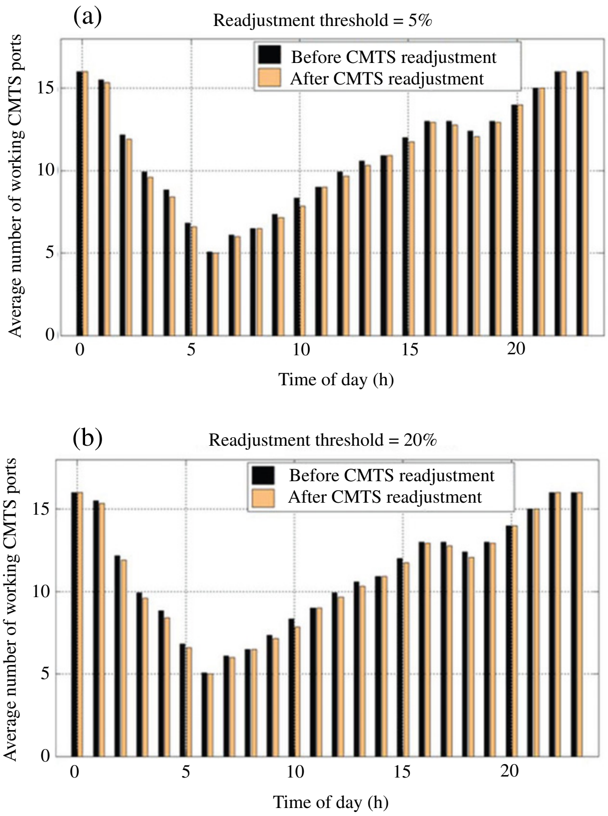

Fig. 10. (Color online) Number of working CMTS ports changing with time, for (a) TH = 5% and (b) TH = 20%.

the cost of more DBC operations (NoOC). Similarly to the CM case, the CMTS energy consumption can be assumed as the product of the number of working ports and the working time. As the readjustment can cause additional NoOC, we investigate the tradeoff between CMTS energy saving and this additional NoOC by running 100 simulations with different values of $TH \in [0, 20\%]$. Figure 11 shows the simulation results. The percentage of energy saving is calculated by comparing to the traditional case without any energy-saving operations. We assume that the energy consumption of one CMTS port operating for an hour is 100 units, and Table III shows the energy consumption values for four operation scenarios. The values are obtained by averaging the results of 32 simulations. The algorithms achieve 31.08%–32.61% energy saving on average. Figure 12 plots the comparisons of CMTS energy saving for two operation scenarios in a 24-h period.

V. Conclusion

We have proposed energy-saving algorithms to improve the energy efficiency of HFC networks that support the DOCSIS 3.0 standard. The algorithms incorporated a traffic-aware approach and modified the operation statuses of the CMs and CMTS dynamically. Energy saving on the CM side was first achieved by dimensioning the CMs' channel sets according to their traffic loads. We then improved the algorithm with traffic prediction and tried to optimize the tradeoff between energy

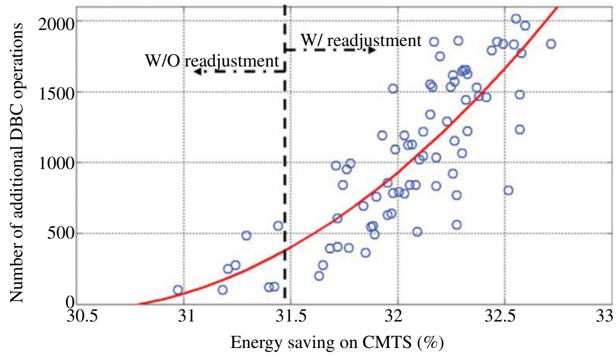

Fig. 11. (Color online) Tradeoff between energy saving and additional NoOC.

Algorithm 3 CMTS-Side Energy-Saving Algorithm

```
while energy-saving feature is ON do
    for all CM_m in the MAC domain do
        run Algorithm 1;
        if |S_{i,m}| > |S_{i-1,m}| then
            add |S_{i,m}| - |S_{i-1,m}| connections to the busiest
            CMTS ports with DBC;
        else if |S_{i,m}| < |S_{i-1,m}| then
            delete |S_{i-1,m}| - |S_{i,m}| connections from the light-
            est CMTS ports with DBC;
        end if
        sort CMTS ports based on the number of active
        connections;
    end for
    for all CMTS ports from lightest to busiest do
        if L_{i,j} ≤ TH then
            redistribute connections on current port to busier
            ones with DBC;
        else
            break the loop;
        end if
        if L_{i,j} = 0 then
            put current port into sleep mode;
        end if
        sort CMTS ports based on the number of active
        connections;
    end for
    Wait(Δt);
end while
```

saving and other performance parameters, such as packet delay and NoOC. Both average and weighted prediction scenarios were investigated, and a multi-objective optimization with simulated annealing was proposed to find the coefficients for weighted prediction. The CM-side energy-saving algorithms were then evaluated with simulations using a realistic traffic model for HFC networks. The simulation results showed that 37.5%–42.2% energy saving could be achieved on the CM side compared to the traditional case where the CMs' operation statuses were static. We then moved to the CMTS side and proposed energy-saving algorithms to find the actual connection mapping between CMs' channels and CMTS ports. The proposed algorithms could support CM connections with the minimal numbers of CMTS ports. A CMTS readjustment

TABLE III
SIMULATION RESULTS FOR CMTS ENERGY CONSUMPTION

	Traditional case	No readjustment	Readjustment with TH = 10%	Readjustment with TH = 20%
Energy (units)	38,400	26,464	26,091	25,878
Energy saving (units)	0	11,936	12,309	12,522
Energy saving (%)	0	31.08	32.05	32.61

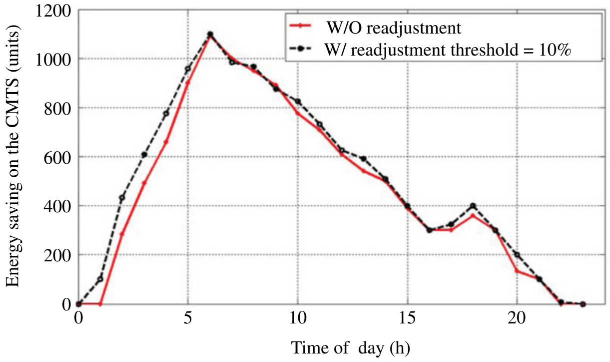

Fig. 12. (Color online) Comparisons of energy saving on the CMTS.

scenario was developed to further improve the energy saving. The simulation results showed that the CMTS-side algorithms achieved 31.08%–32.61% energy saving compared to the traditional case. The proposed algorithms achieved effective energy saving on both the CM and CMTS sides, and hence provide cable operators with a promising way to reduce the OPEX and environmental impacts of their HFC networks.

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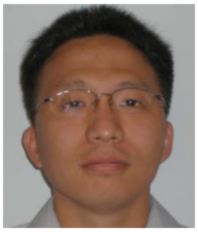

Zuqing Zhu received his Ph.D. degrees from the Department of Electrical and Computer Engineering, University of California, Davis, in 2007. From July 2007 to January 2011, he worked in the Service Provider Technology Group of Cisco Systems, San Jose, as a Senior R&D Engineer. In January 2011, Dr. Zhu joined the University of Science and Technology of China (USTC), as an Associate Professor. His research interests are energy-efficient network designs, access network technologies, and optical communications and networks. He has published more than 60 papers in the journals and conferences of IEEE, IEE, and OSA. Dr. Zhu has been on the technical program committees (TPC) of INFOCOM, ICC, GLOBECOM, ICCCN, etc. Dr. Zhu is also an Editorial Board member of *Elsevier Journal of Optical Switching and Networking* (OSN), *Springer Telecommunication Systems Journal* (TSMJ), *Wiley European Transactions on Emerging Telecommunications Technologies* (ETT), etc. He is a member of IEEE and OSA.