A Novel Energy-Aware Design to Build Green Broadband Cable Access Networks

Zuqing Zhu, *Member, IEEE*

***Abstract*—We propose and investigate energy-saving algorithms for DOCSIS-3.0 networks. By proactively monitoring traffic load, the algorithms achieve network-wide energy saving by re-adjusting CM's bonding groups and shutting down under-utilized upstream/downstream ports on the CMTS. Numerical simulations indicate that by applying the CM side algorithm only, we can achieve a possible 17.6% energy saving for 8192 CMs. We also study the fundamental tradeoff between energy-saving and packet queuing delay and estimate the upper bounds of the delays.**

***Index Terms*—Cable access networks, hybrid fiber coaxial (HFC) networks, DOCSIS 3.0, energy-aware design, green networks.**

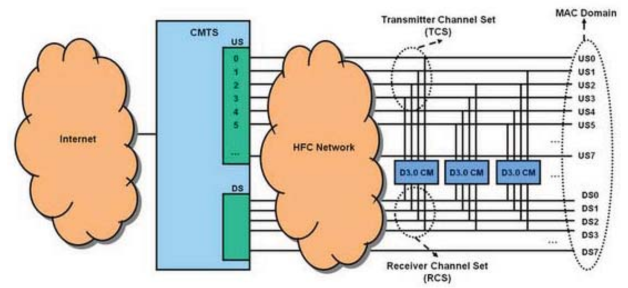

Fig. 1. Infrastructure of DOCSIS 3.0 network, CMTS: cable modem termination system, HFC network: hybrid fiber coaxial network, D3.0: DOCSIS 3.0, CM: cable modem, US: upstream, DS: downstream.

I. Introduction

ENERGY consumption of information and communication technology (ICT) is increasing rapidly every year, especially for the access networks [1, 2]. Data over Cable Service Interface Specification (DOCSIS) is an international industry standard that supports broadband Internet access over the hybrid fiber coaxial (HFC) infrastructure for existing Cable TV (CATV) systems. While new technologies in DOCSIS network boost the network performance, they also result in higher energy consumption. One example is the channel bonding technology, which was released in DOCSIS 3.0 [3]. It achieves over 100 Mbps speed for both downstream (DS) and upstream (US) data transmissions. Specifically, multiple 6 or 8 MHz channels are combined into one virtual channel for high-speed transmission. Channel bonding increases the power consumption on both the Cable Modem Termination Systems (CMTS) and Cable Modems (CM). On the CM side, multiple transceivers are turned on to accommodate US and DS bonding. On the CMTS side, equipment vendors have to develop CMTS linecards with increased number of US/DS ports, which result in additional power consumption.

In this letter, we present adaptive, traffic-aware, coordinated algorithms to reduce power consumption in DOCSIS 3.0 networks. By proactively monitoring traffic load, the proposed algorithms achieve network-wide energy saving by re-adjusting CM's bonding groups and shutting down under-utilized US/DS ports on the CMTS. With a realistic traffic model, the proposed algorithms demonstrate effective energy saving. The algorithms' impact on the packet queuing delay is also investigated. The simulation results indicate that there is a fundamental trade-off between the energy saving and the queuing delay.

Manuscript received March 18, 2011. The associate editor coordinating the review of this letter and approving it for publication was A. Shami.

Z. Zhu was with Cisco Systems, 375 East Tasman Drive, San Jose, CA 95134, USA. He is now with the School of Information Science and Technology, University of Science and Technology of China, Hefei, Anhui, 230027, P. R. China (e-mail: zqzhu@ieee.org).

Digital Object Identifier 10.1109/LCOMM.2011.060811.110591

II. DOCSIS 3.0 Networks

Figure 1 shows the architecture of a typical DOCSIS 3.0 network. The wideband CM is equipped with multiple transceivers, and can tune to multiple US/DS channels from the CMTS simultaneously. The CMTS groups its US and DS ports into MAC domains that each usually contains 8 US and 8 DS ports. The DOCSIS 3.0 standard defines the set of US/DS ports that a CM uses in a MAC domain as its transmitter channel set (TCS)/receiver channel set (RCS) [3]. A MAC-layer operation, dynamic bonding change (DBC), can adjust the TCS/RCS of a CM without introducing significant traffic disruption [3].

III. Energy-Aware Design

Due to the life style of human beings, the traffic in a DOCSIS network can have relatively large hourly fluctuations [4]. This fact suggests that certain network elements in a DOCSIS 3.0 network may be underutilized or idle during low-traffic hours, such as from 4:00 to 7:00 am. Therefore, if we selectively shut down or put them into idle state, network-wide energy saving can be achieved. Our proposed energy-saving algorithms have a two-step coordinated operation, one for the CM side and the other for the CMTS side.

A. CM Side Energy-Saving Algorithm

The CM side algorithm defines three CM operation modes: 1) high-power mode with a 4×4 configuration, 2) moderate-power mode as 2×2; and 3) low-power mode as 1×1. Note that the configuration $n \times n$ here means the CM connecting to n DS and n US ports. For simplicity, we assume the trend of US traffic fluctuation mimics that of the DS, which is usually the case in a real DOCSIS networks [4]. Hence, the CMTS maintains two DS traffic-load thresholds for the CMs: high-watermark (HW) and low-watermark (LW). When the asymmetry of DS and US traffic has to be addressed, a more sophisticated algorithm can be developed to treat the DS and US separately with the similar logic.

Algorithm 1 Coordinated CM Side Energy-Saving Algorithm

Input: Operation modes of CMs, HW, and LW
Output: Operation modes of CMs for energy-saving
Operations:
FOR all the CMs
  Measure current DS traffic load $L_{current}(i, m)$;
  Calculate average traffic load $L_{average}(m)$;
  IF $L_{current}(i, m) \geq$ HW
    Change CM to high-power mode;
  ELSE IF $L_{current}(i, m) < HW$ **AND** $L_{current}(i, m) \geq$ LW
    IF CM in low-power mode
      Change CM to moderate-power mode;
    ELSE IF CM in high-power mode **AND** $L_{average}(m) < HW$
      Change CM to moderate-power mode;
    ELSE
      Keep CM mode unchanged;
  ELSE
    IF CM not in low-power mode
      IF $L_{average}(m) < HW$ **AND** $L_{average}(m) \geq LW$
        Change CM to moderate-power mode;
      ELSE IF $L_{average}(m) < LW$
        Change CM to low-power mode;
      ELSE
        Keep CM mode unchanged;
    ELSE
      Keep CM mode unchanged;

As illustrated in Algorithm 1, the CMTS maintains two variables for each CM, the current traffic load

$$X_{i,m} = L_{current}(i, m) \quad (1)$$

and the average traffic load

$$Y_{i,m} = L_{average}(m) = \frac{1}{N} \sum_{j=i-N}^{i} X_{j,m} \quad (2)$$

where i is the sampling point and m is the CM's ID. With a fixed time interval (a few minutes), the CMTS determines $X_{i,m}$ of CMs by measuring the length of corresponding input queues. The CMTS only reduces the size of CM's TCS and RCS when the average load is below the thresholds. The settings are restored immediately when the current traffic load exceeds the thresholds. Therefore, minimal impact to the CM's legacy traffic can be achieved. From Algorithm 1, we can derive that after *i-th* sampling, CM's possibility at certain power mode is:

$$\begin{aligned} P_H &= P(X_{i,m} \geq HW) + P(Y_{i,m} \geq HW) - \\ &\quad P(X_{i,m} \geq HW)P(Y_{i,m} \geq HW) \\ P_M &= P(X_{i,m} \in [LW, HW))P(Y_{i,m} < HW) + \\ &\quad P(X_{i,m} < LW)P(Y_{i,m} \in [LW, HW)) \\ P_L &= P(X_{i,m} < LW)P(Y_{i,m} < LW) \end{aligned} \quad (3)$$

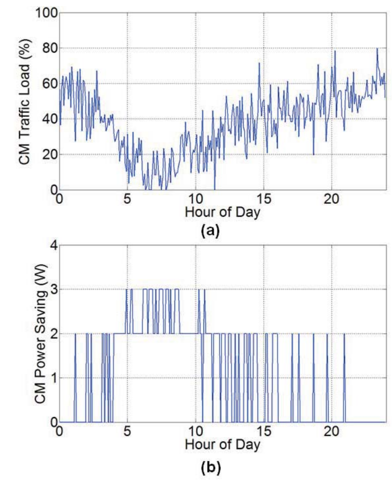

Fig. 2. Simulation results for: (a) a CM's traffic load variation; (b) power saving achieved on a CM.

If we assume the power consumption of a CM follows the expression:

$$PW_m(t) = PW_{0,m} + n_m(t)PW_{c,m} \quad (4)$$

where $PW_{0,m}$ is the static power consumption of the CM, $n_m(t)$ is the number of the transceivers the CM is using at moment *t*, and $PW_{c,m}$ is the dynamic power consumption for one transceiver. $n_m(t)$ is usually four in the normal operation. If the CMTS uses DBC to remove one US/DS channel from a CM's TCS/RCS, the CM will not transmit/receive any control messages, such as ranging messages, scheduling messages and etc, or data packets on that particular channel. Thus, the transceiver for that channel is in an idle mode to save $PW_{c,m}$.

B. Simulations for CM Side Energy-Saving

Simulations are then performed to use a realistic DOCSIS traffic model with self-similarity [4]. Figure 2(a) shows the simulated traffic load of a CM in terms of its capacity. The CMTS samples the traffic every 5 minutes and calculates the average load over 10 minutes, and CM operation is then changed according to Algorithm 1. We use the traditional scheme where CM always operates in 4×4 configuration as reference. Figure 2(b) plots the power saved for the CM over the day with $PW_{0,m} = 5W, PW_{c,m} = 1W, HW = 50\%, LW = 25\%$.

To simulate the CMs from different vendor, we assume $P_{0,m}$ and $P_{c,m}$ are uniformly distributed in [5 W, 9 W] and [1 W, 2 W], respectively. The CMTS system in the simulation has four MAC domains that host 8192 CMs in total. The CMs have independent traffic loads with similar overall trend. Figure 3(a) shows the hourly energy-saving in total for 8192 CMs. Results from 32 simulations are plotted to show the statistical accuracy and the dash-line indicates the average saving. Figure 3(b) investigates the relation between the energy saving and the averaging time period for calculating $L_{average}(m)$. As

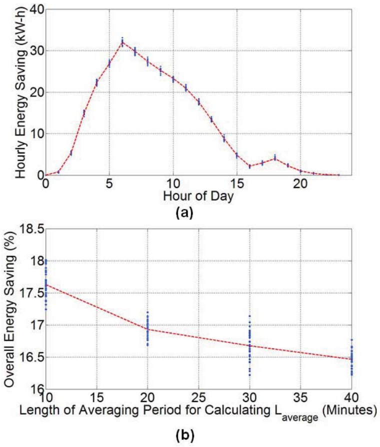

Fig. 3. (a) Hourly energy savings from 8192 CMs; (b) traffic load averaging period versus energy saving.

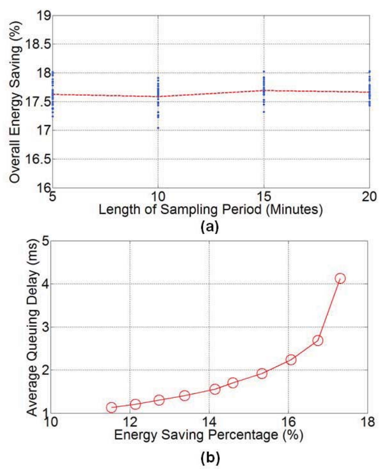

Fig. 4. (a) Length of sampling period versus overall energy saving for 8192 CMs; (b) average queuing delay versus CM energy saving percentage.

expected, shorter averaging period gets better energy saving, since the CM configuration follows the traffic load change more quickly. While shorter averaging period also cause CM oscillates between different power modes more frequently. Our proposed scheme can achieve 17.6% energy saving in average with an averaging period of 10 minutes. Figure 4(a) shows energy saving vs. length of sampling period.

Adopting an M/M/1 queuing model, we can approximate the queuing delay as:

$$T_m(t) = \frac{S_{avg}}{C_{max}} \frac{1}{(N_m(t)/4 - L_{current}(t,m))} \tag{5}$$

where S_{avg} is the average packet size, and C_{max} is the channel capacity. We adopt S_{avg} as 1518 bytes and use this maximum Ethernet packet length to calculate the upper-bound of queuing delay. The C_{max} is set at 30 Mb/s as the DS peak rate of a 4-channel bonding CM from subscription. We then vary the traffic thresholds (i.e., HW and LW) to investigate the tradeoff between energy-saving and queuing delay. Figure 4(b) shows that the queuing delay increases with the energy saving.

C. CMTS Side Energy-Saving Algorithm

The CMTS grooms as many CMs on minimal number of ports as possible, and shut down the rest of the ports to save energy. We define two CM count thresholds: high-watermark (N_HW) and low-watermark (N_LW), for each port. The simulation results of the CMTS side algorithm are omitted due to space limit.

Algorithm 2 Coordinated CMTS Side Energy-Saving Algorithm

Input: Number of CMs on each port, N_HW and N_LW.
Output: Operation of the CMTS for energy-saving
Operations:
FOR all US/DS ports in the MAC-domain
  IF $N(t) < N\_LW$
    IF there is still room on other active port(s)
      Move CMs to other port(s);
      Shut down this port;
    ELSE
      Make no change;
  ELSE IF $N(t) \geq N\_HW$
    IF there is still room on other active port(s)
      Move CMs to other port(s) until
      $N(t,n) = N\_HW - 1$;
    ELSE
      Turn on an inactive port;
      Move CMs to the port newly on until
      $N(t) = N\_HW - 1$;
  ELSE
    Make no change;

IV. Summary

We proposed a novel technology to achieve coordinated energy saving in DOCSIS 3.0 networks. The technology includes two algorithms, one for the CM side and the other for the CMTS. With a realistic DOCSIS traffic model, we demonstrated a possible 17.6% overall CM energy saving in a simulation of 8192 CMs. The tradeoff between the energy saving and the packet queuing delay on the CM was also investigated. A maximum queuing delay of 4.15 msec had been obtained at the highest energy saving. While these results are specific to the configuration and assumptions of out model, the basic conclusion is that the adaptive algorithms can potentially conserve a significant amount of energy.

References

[1] L. Valcarenghi, *et al.*, “Energy efficient optical access and metro networks,” in *Proc. ICTON 2010*, paper Tu.B1.2.
[2] C. Lauge, *et al.*, “On the energy consumption of FTTH access networks,” in *Proc. OFC*, paper JThA79, Mar. 2009.
[3] http://www.cablelabs.com/
[4] M. Garcia, *et al.*, “Analysis and modeling Of traffic on a hybrid fiber-coax network,” *IEEE J. Sel. Areas Commun.*, vol. 22, pp. 1718-30, Nov. 2004.