Energy-Efficient Scheduling and Energy-Delay Tradeoff in Green Hybrid Fiber-Coaxial Networks

Ping Lu[1], Yabo Yuan[1], Farid Farahmand[2], Joel J. P. C. Rodrigues[3], Zuqing Zhu[1,*]
[1]School of Information Science and Technology, University of Science and Technology of China, Hefei, China
[2]Department of Engineering Science, Sonoma State University, USA
[3]Department of Informatics, University of Beira Interior, Portugal
*Email: {zqzhu}@ieee.org

***Abstract*—Hybrid Fiber Coaxial (HFC) networks support broadband Internet access with the existing cable TV systems. Recent advances on HFC networks have demonstrated effective improvements on the customers' access speeds with the channel-bonding technology. In this paper, we develop a novel energy-efficient traffic scheduling algorithm for the HFC networks that support channel bonding. The proposed algorithm is compliant with the newly-released DOCSIS 3.0 standard.**

We come up with a system model of the channel-bonding transmitters (TXs) on a Cable Modem (CM), and then define several operation modes for them. At the beginning of each scheduling cycle, the proposed algorithm adjusts the TXs' operation modes based on the traffic status. Both analytical analysis and numerical simulations are then developed to investigate the energy-saving and delay introduced by the algorithm. The results on energy-saving indicate that the energy-consumption of the TXs scales almost linearly with the input traffic load and effective energy-saving can be achieved. We also investigate the tradeoff between the energy-saving and the average delay to optimize the parameters for the energy-efficient scheduling, and to make sure that the traffic will not experience significant delay increase due to the energy-saving operations.

***Index Terms*—Hybrid fiber-coaxial (HFC) networks, DOCSIS 3.0 standard, Energy-efficient scheduling, Energy-delay tradeoff**

I. INTRODUCTION

As the Internet is evolving towards Web 2.0, bandwidth-hungry applications emerge rapidly and have spurred fast scaling of the network infrastructures. Meanwhile, the rising trend of equipment installations makes the energy consumption of network systems a global concern. It was estimated that the Information and Communication Technology (ICT) accounts for $\sim$2% of the total carbon emission produced by human activities [1]. Recent investigations indicated that the majority of the Internet's energy consumption is from the access networks, and this situation will not change in the short-to-middle-term future [2]. One significant example is the deployments and upgrades of the broadband access networks, as the network operators and service providers have invested heavily in this area to facilitate higher-speed customer access.

Recently, various energy-efficient technologies have been proposed for different types of broadband access networks [3-7]. In [3], Blume *et al.* proposed to improve the energy-efficiency of mobile access networks (e.g. 3G/4G systems) with smart transmission technologies in small cells using MIMO. Green Digital Subscriber Line (DSL) technology has been demonstrated by using dynamic spectrum management in [4]. By incorporating traffic-aware mechanisms and sleep-modes, energy-efficient network designs have been developed for Hybrid Fiber Coaxial (HFC) networks [7], Passive Optical Networks (PON) [5], and Hybrid Wireless-Optical Broadband Access Networks (WOBAN) [6].

A. HFC Networks

Hybrid Fiber Coaxial (HFC) networks support broadband Internet access with the existing cable TV systems. As shown in Fig. 1, the HFC network has an infrastructure that combines optical fibers and coaxial cables, and digitally modulated signals are delivered through RF TV channels. Downstream (DS) traffics from the cable operator's headend are distributed through optical fibers to the optical nodes, where they experience optical-to-electrical conversions, and are then sent to the customers through a tree network of coaxial cables [8]. Upstream (US) traffics from the customer premises equipments are transmitted in the opposite direction.

Data over Cable Service Interface Specifications (DOCSIS) [8] is the international industry standard for developing HFC network equipments. DOCSIS allocates US and DS traffics to different frequency ranges. The frequency ranges are further divided into RF channels with a 6 or 8 MHz bandwidth, and customer premises equipments share these channels in a Time-Division Multiplexing (TDM) manner. DOCSIS defines two primary network elements in HFC networks, the Cable Modem Termination System (CMTS) located at the operator's head-end, and the Cable Modem (CM) at the customer's premises. The CMTS packs DS traffics to different CMs in different time slots on the DS channels, while in the US direction, the CMs request for future transmission opportunities and CMTS grants US time slots using a scheduling algorithm.

B. DOCSIS 3.0 and Channel Bonding

DOCSIS 3.0 standard [8] has been released recently. It redefined the communications between the CMTS and CM for higher throughput, and provided cable operators a remarkable opportunity to outpace competitors such as the Fiber-to-the-Home (FTTH) providers. Specifically, multiple US or DS channels can be bonded together and work as a virtual broadband channel. As shown in Fig. 2(a), this channel bonding technology can push the throughput to 100 Mb/s or more.

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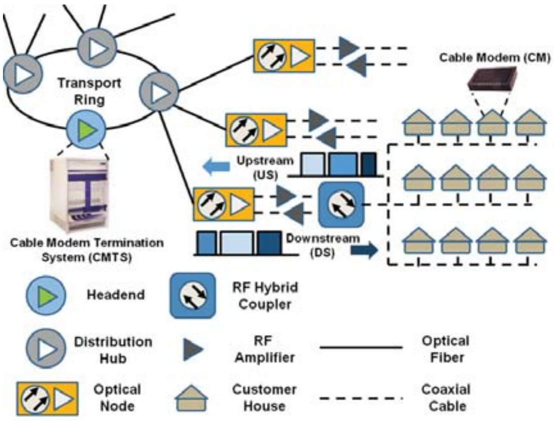

Fig. 1. HFC network infrastructure.

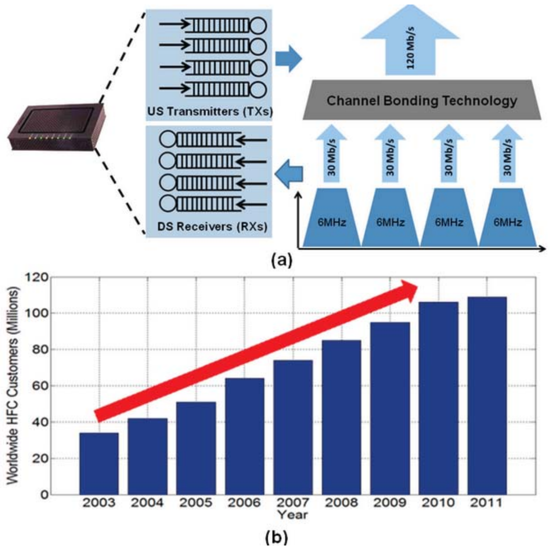

Fig. 2. (a) Channel bonding in DOCSIS 3.0, (b) Worldwide HFC customers.

While the channel bonding technology boosts up the network throughput effectively, it also leads to significant power consumption increase on both the CMTS and CM. The CM will be equipped with multiple RF transmitters (TX) and receivers (RX) that consume more power, while the CMTS will have increased numbers of US/DS ports for accommodating the channel bonding requirement.

As we can see in Fig. 2(b), the number of worldwide HFC customers increases consistently in the last decade. If we assume the average power consumption per customer is 13.2 Watts [2], the increase of HFC networks' power consumption has been $\sim$66 million Watts from 2010 to 2011. On the other hand, since the HFC networks are usually dimensioned according to peak traffic loads, significant energy is wasted when the equipments are idling during the low-traffic hours, such as 4 $\sim$ 7 am [9].

C. Related Works and Our Contributions

Recently, we have reported several traffic-aware algorithms that could improve the energy-efficiency of HFC networks based on DOCSIS 3.0 [7,10,11]. We employed cooperative approaches and achieved energy-saving by putting unused TXs and RXs into the sleep-mode, on both the CMTS and CMs sides. However, the algorithms did not consider traffic scheduling on the channel level, and the performance evaluations of the energy-delay tradeoff were based on an over-simplified M/M/1 queuing model. Further investigation is still necessary to explore the energy-efficient traffic scheduling algorithm on the bonding-channel level, and to analyze the energy-delay tradeoff in depth.

Choi *et al.* proposed several adaptive sleep scheduling protocols for Delay Tolerant Networks (DTN) in [12]. With hierarchical arrangements of cyclic different sets, the energy efficiency of DTNs could be improved with proper designs of frame structure, neighbor discovery, etc. In [13], a score-based energy-efficient scheduling algorithm was proposed for Long Term Evolution (LTE) systems. The frequency resource was allocated in an energy-efficient way, and the proposed algorithm traded bandwidth for energy-efficiency during low-traffic periods. The energy-efficient scheduling of periodic real-time tasks was address in [14] for lightly loaded multi-core processors. Two energy-saving techniques were introduced, exploiting idle cores for executing a task in parallel with a reduced frequency, and shutting down idle cores. Miao *et al.* proposed a low-complexity energy-efficient scheduling algorithm for cellular networks employing OFDMA in [15]. By considering the time-averaged bit-per-Joule metrics, the algorithm allocated bandwidth resource in a way that energy-efficiency could be optimized across the network. HFC networks have unique attributes, such as adaptive channel bonding, special MAC control protocols, bursty traffic with relatively large hourly fluctuations, etc. Hence, it will be difficult to apply the above proposals to HFC networks, especially for those who support DOCSIS 3.0.

In this paper, we develop a novel energy-efficient traffic scheduling algorithm for HFC networks supporting DOCSIS 3.0, which can adaptively assign data traffic to different channel-bonding TXs with the consideration of traffic status. Specifically, several operation modes are defined for the TX on a CM, and at the beginning of each scheduling cycle, the algorithm adjusts the TXs' operation modes based on the status of input traffic queues. Based on the proposed algorithm, the energy-delay tradeoff is investigated with both analytical analysis and numerical simulation. The results indicate that with the energy-efficient scheduling, the energy-consumption of the TXs scales almost linearly with the input traffic load and effective energy-saving can be achieved. We also investigate the tradeoff between the energy-saving and the average delay to optimize the parameters for the energy-efficient scheduling.

The rest of the paper is organized as follows. Section II discusses the problem formulation of energy-efficient scheduling for CMs' TXs in HFC networks. We explain the details

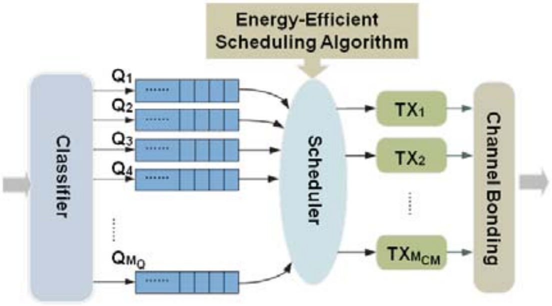

Fig. 3. System model of the channel-bonding transmitters that use energy-efficient scheduling.

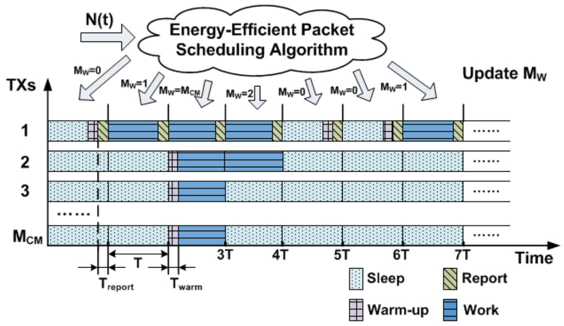

Fig. 4. Time diagram of energy-efficient traffic scheduling.

of the proposed energy-efficient traffic scheduling algorithm in Section III. The analytical derivations of the energy-saving and delay introduced by the proposed algorithm is illustrated in Section IV. Section V describes the numerical simulations for performance evaluation and algorithm optimization. Finally, Section VI summarizes the paper.

II. PROBLEM FORMULATION

As the CMs usually contribute to more than 50% of the per-user power consumption in HFC networks [2], we focus on the CM-side and propose an energy-efficient traffic scheduling algorithm for the US transmission. Note that with minor modifications, the proposed algorithm can also be applied to the CMTS-side for energy-saving of the DS transmission. Fig. 3 shows the system model of the US channel-bonding data transmission. According to the DOCSIS 3.0 standard [8], the traffic classifier can differentiate the incoming traffic into M_Q priority queues based on their Service Flow IDs. We assume that for each priority i, the traffic-arrival follows the Poisson process with different rates λ_i, $i = 1, 2, ..., M_Q$, and the service time per data unit is μ_s for each TX. The energy-efficient scheduling algorithm determines the operation mode of a channel-bonding TX based on the status of the priority queues, and forwards data in the queues to a proper TX.

Definition 1 (TX Operation Modes). We define three operation modes for a channel-bonding TX: 1) Working, as it is transmitting data and the power consumption of this mode is denoted as P_{work}, 2) Sleeping, as it is in the energy-saving mode with a power consumption of P_{sleep}, and 3) Warming-up, as it is waking up from the sleeping mode and the power consumption is P_{warm}.

Definition 2 (Queue Length for Decision). The energy-efficient scheduling algorithm determines the operation modes of the TXs based on the Queue Length for Decision $N(t)$ as

$$N(t) = \sum_i N_i(t) \tag{1}$$

where t is the time instant, and $N_i(t)$ is the length of queue Q_i at t.

Definition 3 (Turn-ON Threshold per TX). We define the Turn-ON Threshold per TX as a constant N_T, and use it to determine the number of working TXs M_W for the next scheduling cycle

$$M_W = \begin{cases} \lfloor \frac{N(t)}{N_T} \rfloor, & \lfloor \frac{N(t)}{N_T} \rfloor \le M_{CM} \\ M_{CM}, & \lfloor \frac{N(t)}{N_T} \rfloor > M_{CM} \end{cases} \tag{2}$$

where M_{CM} is the maximum TXs the CM can turn on for the working mode.

Definition 4 (Scheduling Cycle). The energy-efficient scheduling algorithm adjusts the value of M_W in each Scheduling Cycle

$$T = N_T \cdot \mu_s \tag{3}$$

Here, T can be the MAP Time, and its definition complies with the DOCSIS 3.0 standard [8].

Definition 5 (CM Utilization Ratio). We define the utilization ratio of a CM as

$$\rho = \frac{\lambda \cdot \mu_s}{M_{CM}}, \lambda = \sum_{i=1}^{M_Q} \lambda_i \tag{4}$$

where λ is the total traffic-arrival rate.

III. ENERGY-EFFICIENT TRAFFIC SCHEDULING ALGORITHM

Fig. 4 shows the time diagram of the energy-efficient traffic scheduling. The scheduler on the CMTS determines M_W for each CM based on Eqn. (2) and sends the corresponding instruction out using DS control messages. According to these messages, a CM sets the operation modes of its TXs at the beginning of each Scheduling Cycle. If a TX needs to be waken up, it goes through the Warming-up mode and starts to transmit data in the Working mode. We assume the Warming-up takes a fixed amount of time as T_{warm}. If a TX has been in the Working mode for k cycles, the total working time is $kT - T_{warm}$. Hence, the energy consumption for these k cycles is

$$E = (kT - T_{warm})P_{work} + T_{warm}P_{warm} \tag{5}$$

If a TX has been in the Sleeping mode for k cycles, the total sleep time is kT and the energy consumption is

$$E = kTP_{sleep} \tag{6}$$

The operation of the TX with the lowest index (TX_1) is unique, as it has to transmit necessary US control messages (e.g. bandwidth requests) towards the end of every Scheduling Cycle. Note that if TX_1 has been in the Sleeping mode for the cycle, it will be waken up. We assume that TX_1 uses a fixed amount of time T_{report} to transmit the control messages. Hence, when TX_1 has been in the Sleeping mode for a cycle, its energy consumption is $(T - T_{warm} - T_{report})P_{sleep} + T_{warm}P_{warm} + T_{report}P_{work}$; otherwise, when it has been in the Working mode, its energy consumption is TP_{work}.

Algorithm 1 shows the detailed procedures of the energy-efficient traffic scheduling. When transmitting the data, the TXs handle those with a higher priority i earlier according to the non-preemptive rule. To prevent the data being buffered too long, we introduce K_{max} as the maximum number of continuous Sleeping cycles that TX_1 can stay in when there is pending data in the queues.

IV. ANALYTICAL DERIVATIONS

A. Energy Saving

In the CM operation without the energy-efficient scheduling, all of the TXs are in the Working mode, and its average energy-consumption in a Scheduling Cycle is

$$\overline{E_{norm}} = M_{CM} \cdot P_{work} \cdot T \tag{7}$$

While under the energy-efficient scheduling, the average energy-consumption can be formulated as

$$\overline{E_{eff}} = \sum_{m=0}^{M_{CM}} Prob(m)\overline{E(m)} \tag{8}$$

where $Prob(m)$ and $\overline{E(m)}$ are the probability and average energy-consumption per T for the case $M_W = m$, respectively. In the practical operation of a CM's TX, $T \gg T_{warm}$ is usually the case and thus we assume $T_{warm} \to 0$ for simplifying the analytical derivations. For $M_W = 0$,

$$\begin{aligned} E(0, work) &= P_{work}T + (M_{CM} - 1)TP_{sleep} && (9) \\ E(0, sleep) &= (T - T_{report})P_{sleep} + T_{report}T_{work} \\ &\quad +(M_{CM} - 1)TP_{sleep} && (10) \end{aligned}$$

where $E(0, work)$ and $E(0, sleep)$ are the energy per T that TX_1 is in the Working and Sleeping mode for the $M_W = 0$ case, respectively. For $M_W = m(m > 0)$

$$\overline{E(m)} = mTP_{work} + (M_{CM} - m)TP_{sleep} \tag{11}$$

Combine Eqn. (4) and (8)-(11) and consider the Poisson traffic model, we can get an approximation of $\overline{E_{eff}}$ as

$$\begin{aligned} \overline{E_{eff}} &\approx M_{CM}T((1 - \rho)P_{sleep} + \rho P_{work}) \\ &\quad +T_{report}(P_{work} - P_{sleep}) && (12) \end{aligned}$$

Algorithm 1 Energy-Efficient Traffic Scheduling Algorithm

```
$M_W^{old} = 0$, $k = 0$;
while CM is operational do
    measure $N(t)$;
    determine $M_W$ based on Eqn. (2);
    if $M_W = 0$ then
        if $k = K_{max}$ then
            $TX_1 \to$ Working;
            transmit control messages;
            if $min(Size(Q_i), \forall i) > 0$ then
                transmit all pending data based on their priorities;
            end if
            $k = 0$;
        else
            $TX_m \to$ Sleeping ($m = 2, ..., M_W^{old}$);
            $TX_1 \to$ Working;
            transmit control messages;
            $TX_1 \to$ Sleeping;
            $k = k + 1$;
        end if
    else
        $k = 0$;
        if $M_W > M_W^{old}$ then
            $TX_m \to$ Working ($m = M_W^{old} + 1, ..., M_W$);
            transmit control messages;
            transmit pending data based on their priorities;
        else if $M_W < M_W^{old}$ then
            $TX_m \to$ Sleeping ($m = M_W^{old} + 1, ..., M_W$);
            transmit control messages;
            transmit pending data based on their priorities;
        else
            transmit control messages;
            transmit pending data based on their priorities;
        end if
    end if
    $M_W^{old} = M_W$;
    $wait(T)$;
end while
```

B. Delay

The delay caused by the energy-efficient scheduling can be analyzed with a time-varying M/D/m queuing model (*i.e.*, arrival rate in exponential distribution, deterministic departure rate, and m service channels). Due to the reason that there is no close-form expression for the delay of time-varying M/D/m queue [16], we estimate the average delay $\overline{D(m)}$ for different CM operation mode $M_W = m$. Therefore, for a traffic load ρ, the average delay $\overline{DL}$ is within $[\overline{D(m)}, \overline{D(m+1)}], m = \lfloor \rho M_{CM} \rfloor$. For $m = 0$, TX_1 can not sleep for more than $K_{max}T$, and hence

$$\overline{D(0)} \approx \frac{1}{1 - \rho M_{CM}}[\frac{1}{2}\mu_s \rho M_{CM} + \frac{K_{max}\lambda T - 1}{2\lambda(K_{max} + 1)}K_{max}] \tag{13}$$

For $m > 0$, operation can be approximated as a steady M/D/m queue. As the average delay of a steady M/D/m queue can be estimated with that of a M/M/m queue (*i.e.*, arrival/departure rates in exponential distribution and m service channels) [16], we first determine the average delay of the M/M/m queue as [17]

$$\overline{D^{M/M/m}(m)} = \frac{(\rho M_{CM})^m \mu_s}{m!(m-\rho M_{CM})} \cdot \\ \{\frac{m-\rho M_{CM}}{m}\sum_{n=0}^{m-1}\frac{(\rho M_{CM})^n}{n!} + \frac{(\rho M_{CM})^m}{m!}\}^{-1} \quad (14)$$

Then, we can get $\overline{D(m)}, m > 0$ as [16]

$$\overline{D(m)} \approx \frac{\overline{D^{M/M/m}(m)}}{2} \cdot \\ \{1 + \frac{(m-\rho M_{CM})(m-1)(\sqrt{4+5m}-2)}{16\rho m M_{CM}}\} \quad (15)$$

V. SIMULATIONS AND ALGORITHM OPTIMIZATION

We design numerical simulations to evaluate the performance of the proposed energy-efficient scheduling algorithm. Table I shows the simulation parameters. We define the energy-saving as $1 - (\overline{E_{eff}}/\overline{E_{norm}})$, and start with the case when there is only one traffic priority ($M_Q = 1$). Fig. 5 shows the energy-saving for different values of T, when $K_{max} = 1$. We compare the results from the analytical analysis to those from the numerical simulations. It can be seen that the analytical results match well with the numerical ones, but there are noticeable differences when $\rho \to 0$. The difference is due to the fact that we ignore T_{warm} in the analytical derivations, and when $\rho \to 0$, the Warming-up mode starts to show its effect on energy-saving. Note that with the energy-efficient scheduling algorithm, the energy-consumption of the system scales almost linearly with the traffic load, leading to effective energy-saving. We also notice that the energy-saving starts to show saturation when T reaches 5 time-units.

We then investigate the average delay caused by the energy-efficient scheduling algorithm. Fig. 6 shows the simulation results with $K_{max} = 1$. As expected, the average delay increases when we increase T. It is interesting to notice that the average delay increases relatively fast when $\rho < 0.16$ and this phenomenon becomes more obvious when T becomes larger. This is due to the special handling of TX_1 in the scheduling algorithm. Specifically, data traffic has to share TX_1 with the control messages. When ρ becomes larger, statistically more TXs are turned on and the control messages' effect on delay becomes smaller. We also observe that the average delay approaches to infinity faster for T with a smaller value, and this is also due to the fixed bandwidth allocation to the control messages on TX_1. For example, when $T = 2$, the total available time for data traffic on the TXs per scheduling cycle is $M_{CM}T - T_{report} = 7$ time-units and this means that the data traffic can only occupy 87.5% of the total bandwidth. Hence, for this case, when $\rho \to 0.875$, the average delay approaches to infinity. When fix ρ at different values, the energy-delay tradeoff can be plotted by changing T. Fig. 7 illustrates the energy-delay tradeoff by changing T when $K_{max} = 1$. It can be seen that for different traffic load ρ, a reasonably good energy-delay tradeoff can be achieved at $T = 4$, after this point the average delay increases rapidly for just a small amount of energy-saving improvement. Fig. 8 shows the effect of K_{max} on the energy-delay tradeoff when $T = 4$. As expected, K_{max} can affect the average delay when the traffic load is relatively low.

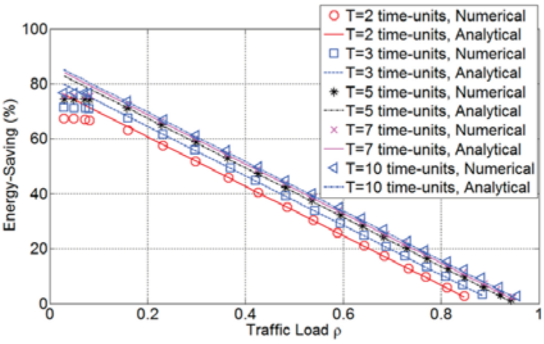

Fig. 5. Energy-saving achieved by the energy-efficient scheduling for different T (single traffic priority).

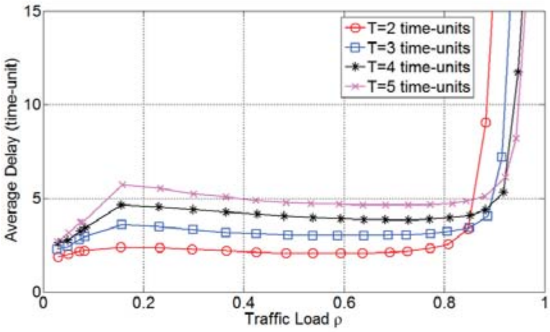

Fig. 6. Average delay with the energy-efficient scheduling for different T (single traffic priority).

We also simulate the case with three traffic priorities, and Fig. 9 plots the average delays of the traffic in Q_1, Q_2 and Q_3, when assuming $\lambda_1 = \lambda_2 = \lambda_3$, $T = 4$, and $K_{max} = 1$. The traffic load ρ represents the total traffic load. Since the energy-efficient scheduling always tries to handle traffic with a higher priority, it is interesting to notice that the average delays of Q_1 and Q_2 can stay small while the traffic in Q_3 experiences a much larger average delay. Hence, when energy-efficient scheduling is operational, we can assign the data traffic from delay-sensitive applications to higher priority queues and use the lowest priority queue for the best-effort traffic.

VI. CONCLUSION

We developed a novel energy-efficient traffic scheduling algorithm for the HFC networks that support channel bonding. the proposed algorithm was compliant with the newly-released DOCSIS 3.0 standard. When designing the algorithm, we first

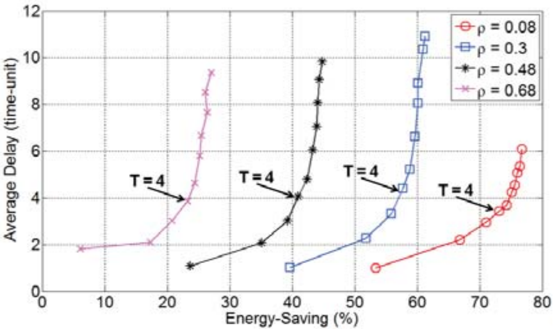

Fig. 7. Tradeoff between average delay and energy-saving for different traffic loads with $K_{max} = 1$ (single traffic priority).

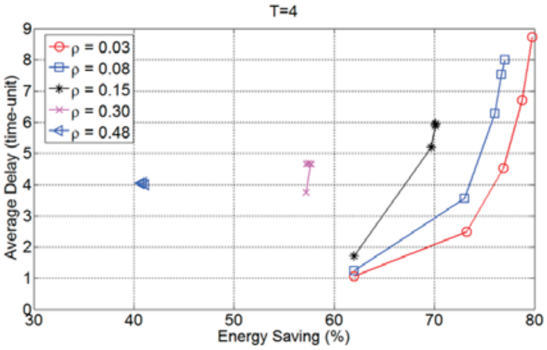

Fig. 8. Tradeoff between average delay and energy-saving for different traffic loads with $T = 4$ (single traffic priority).

came up with a system model of the channel-bonding TXs on a CM, and then defined several operation modes for them. For energy-saving, the proposed algorithm adjusted the TXs' operation modes based on the traffic status at the beginning of each scheduling cycle.

For performance evaluation and optimization of the algorithm, we performed both analytical analysis and numerical simulations to investigate the energy-saving and delay introduced by the algorithm. The results on energy-saving indicated that the energy-consumption of the TXs scaled almost linearly with the input traffic load and effective energy-saving could be achieved. We then investigated the tradeoff between the energy-saving and the average delay to optimize the parameters for the energy-efficient scheduling. When multiple traffic priorities existed, the simulation results showed that we could achieve successful transmission of delay-sensitive traffic together with energy-saving by adjusting the traffic's priority.

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TABLE I
SIMULATION PARAMETERS

P_{work}, one TX's power in Working mode	1 *power-unit*
P_{sleep}, one TX's power in Sleeping mode	0.1 *power-unit*
P_{warm}, one TX's power in Warming-up mode	0.2 *power-unit*
T_{report}, time that TX_1 spends on transmitting control message per scheduling cycle	1 *time-unit*
T_{warm}, time that a TX needs to wake up	0.1 *time-unit*
μ_s, service time per traffic block	1 *time-unit*
ρ, normalized traffic load	$0 \sim 1$
M_{CM}, number of TXs per CM	4
K_{max}, maximum number of continuous Sleeping cycles TX_1 can stay in	$0 \sim 2$
Simulations per data point for statistical accuracy	10

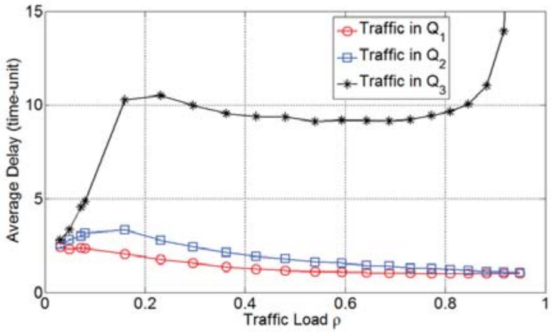

Fig. 9. Average delays for different priority queues with the energy-efficient scheduling for $T = 4$ and $K_{max} = 1$ (three traffic priorities).

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