ABSTRACT

The perpetual growth of the global energy demand not only poses a threat to the scarcity of energy but also increases greenhouse gas emissions which has a serious environmental impact. Information and Communications Technology (ICT) and Internet are one of the major sources of global energy consumption. The exponential growth of Internet users further increases Internet energy consumption. The access network is responsible for consuming 80-90% of overall Internet power consumption. Thus, research on energy-efficient Internet network design is predominantly targeted from the perspective of the access network. The Ethernet Passive Optical Network (EPON), one of the most widely used and adopted access technologies, has made protocol design for energy-efficient EPON a prominent research area. An EPON architecture comprises an Optical Line Terminal (OLT), multiple Optical Network Units (ONUs), and Remote Nodes (RNs). The OLT and ONUs being the active components of EPON, saving energy is targeted from the perspective of the OLT and ONUs. In case of Time Division Multiplexed EPON (TDM-EPON), ONUs are responsible for 60-70% of overall EPON power consumption. Moreover, due to the presence of a single wavelength in TDM-EPON, switching off that wavelength is not possible as control messages are needed to be transmitted. Therefore, in TDM-EPON, energy efficiency is achieved only at ONUs by employing a Low Power Mode (LPM). The protocol for employing LPM at ONU can be managed either by the OLT or by ONUs, based on which these protocols are classified as ONU-assisted and OLT-assisted. In case of TWDM-EPON, due to the presence of multiple wavelengths, at low load, data transmission can be performed using fewer wavelengths, while other wavelengths are switched off to achieve energy efficiency. Thus, in TWDM-EPON, energy efficiency can be achieved at the OLT along with ONUs. Protocols for energy-efficient TDM-EPON can be applied to TWDM-EPON with some minor modifications. Thus, this thesis focuses on achieving energy efficiency at ONUs in TDM-EPON and at the OLT in TWDM-EPON. The first two works of the thesis target saving energy at ONUs in TDM-EPON, while the remaining two works are on achieving energy efficiency in TWDM-EPON.

In the first work, our focus is on designing an ONU-assisted protocol for saving energy at ONU in TDM-EPON. Firstly, a mechanism for employing doze mode during the entire period of other ONUs' up-stream (US) transmission is proposed. Thereafter, an ONU-assisted protocol is proposed. In the suggested strategy, an ONU first predicts the length of its LPM and then chooses the best LPM based on this prediction duration. The above mentioned doze mode implementation technique is used during the active phase. Finally, we mathematically analyze the energy efficiency figure of the proposed ONU-assisted protocol with the help of a Markov model. The traffic prediction process is involved in the proposed protocol, which

infringes the memoryless property making the analysis a hard problem. Some realistic assumptions along with an intelligent selection of discrete observation points and state descriptions aid to eliminate the dependency on the past and allow formulating a Discrete-Time Markov Chain (DTMC) of the proposed protocol.

In the second contribution, an OLT-assisted protocol for saving energy at ONUs in TDM-EPON is proposed, where the duration of LPM of all ONUs is decided such that the minimum number of ONUs wake-up from LPM in a polling cycle. Note that in every cycle, the minimum number of ONUs wakes up from LPM, which implies that the ONUs that are to be awakened within the polling cycles are fairly distributed. To do so, an optimization problem is formulated which distributes the ONUs that are to be awakened fairly among the polling cycles while satisfying the SLA requirements of both US and downstream (DS) traffic. A polynomial times 1-approximation algorithm is proposed, for solving the optimization problem. Moreover, in this work, a method to allow the OLT to force ONUs to wake-up from sleep mode is proposed, which provides additional energy savings. This method requires modification of EPON architecture which is also explained.

The third work focuses on achieving energy efficiency at the OLT receivers in TWDM-EPON. In this work, a novel methodology for an energy-efficient OLT receiver is presented by departing from the traditional approach of minimizing the number of active wavelengths to achieve energy efficiency. In this approach, all wavelengths are utilized for scheduling, and energy efficiency is achieved by switching off OLT receivers within all potential voids (idle times between two consecutive transmission windows). Thus, the number of voids is minimized to maximize energy efficiency, which requires clubbing several smaller voids to form a longer void. With this objective, in this work, a novel online scheduling protocol is proposed. Further, an upper bound on energy efficiency that can be achieved from OLT receivers is derived to demonstrate the deviation of the energy efficiency figure of the proposed protocol from the theoretical upper bound.

By employing the same methodology of minimizing the number of voids, finally a heuristic algorithm to save energy at the OLT transmitters in TWDM-EPON is proposed. Moreover, with the help of a suitable Discrete Time Markov Chain (DTMC) model, a theoretical lower bound of the probability of delay bound violation of the downstream traffic is derived.

Keywords: EPON, Optical network, TDM, TWDM, MAC, access network, DTMC, Low power mode, ONU-assisted, OLT-assisted.