UNIVERSIDADE DE BRASÍLIA
FACULDADE DE TECNOLOGIA
DEPARTAMENTO DE ENGENHARIA ELÉTRICA

ENERGY EFFICIENCY IN NEXT-GENERATION PASSIVE OPTICAL NETWORKS

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DISSERTAÇÃO DE MESTRADO EM
ENGENHARIA ELÉTRICA

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DISSERTAÇÃO DE MESTRADO SUBMETIDA AO DEPARTAMENTO DE ENGENHARIA ELÉTRICA DA FACULDADE DE TECNOLOGIA DA UNIVERSIDADE DE BRASÍLIA, COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE MESTRE EM ENGENHARIA ELÉTRICA.

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RESUMO

ENERGY EFFICIENCY IN NEXT-GENERATION PASSIVE OPTICAL NETWORKS

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Brasília, Novembro de 2014

Nos últimos anos, a eficiência energética tem se tornado um fator cada vez mais importante para as redes de comunicação, principalmente por fatores econômicos e ambientais. Dentre as tecnologias de redes ópticas de acesso existentes, as Redes Ópticas Passivas (*Passive Optical Networks*, PONs) são consideradas as mais eficientes em termos de consumo de energia. Apesar disso, os sistemas PON da ITU-T existentes podem dar suporte a dois modos de economia de potência na unidade de rede óptica (*optical network unit*, ONU), chamados de modos *Doze* e *Cyclic Sleep*, que são mecanismos baseados em protocolos para o gerenciamento de potência. Porém, apesar de estes dois modos terem sido padronizados, não há razão técnica para manter a separação entre eles. Neste trabalho de mestrado, nós apresentamos e avaliamos o desempenho de um novo e único modo de gerenciamento de potência para PONs multiplexadas por divisão de tempo (time division multiplexed, TDM), chamado de modo *Watchful Sleep*, o qual combina as vantagens dos modos *Doze* e *Cyclic Sleep* em um *framework* único e mais simples, e os supera em eficiência energética. Devido à sua eficácia, o modo *Watchful Sleep* foi aprovado para inclusão nos padrões ITU-T G.984 (G-PON) e ITU-T G.987 (XG-PON). Ele também está sendo considerado para inclusão no padrão de NG-PON (ITU-T G.989), cujo objetivo é padronizar as redes TWDM PON.

Palavras Chave: NG-PON2, TWDM-PON, Consumo de Energia e Potência, Modo Watchful Sleep, Modo Unificado.

ABSTRACT

ENERGY EFFICIENCY IN NEXT-GENERATION PASSIVE OPTICAL NETWORKS

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Brasília, November of 2014

Energy efficiency in communication networks has been growing in importance in the last few years, mainly due to economical and environmental issues. Among the existing optical access network technologies, Passive Optical Networks (PONs) are considered the most energy efficient ones. Despite this fact, existing ITU-T PON systems may support two standardized optical network unit (ONU) power saving modes, namely the Doze and Cyclic Sleep modes, which are protocol-based mechanisms for ONU power management. However, notwithstanding that these two modes have been standardized, there is no technical reason to maintain the separation between them. In this master's work, we present and evaluate the performance of a new and single power management mode for time division multiplexed (TDM) PONs, called the Watchful Sleep mode, which combines the advantages of both Doze and Cyclic Sleep modes into a unique and simpler framework and outperforms them in energy efficiency. Due to its effectiveness, the Watchful Sleep mode has been approved to be included in the ITU-T G.984 (G-PON) and ITU-T G.987 (XG-PON) standards. It is also being considered for the NG-PON standard (ITU-T G.989), which aims at standardizing TWDM PON networks.

Keywords: TWDM-PON, Energy and Power Consumption, Watchful Sleep Mode, Unified Mode.

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MAIN ACHIEVEMENTS

A Novel ITU-T Standard for ONU Power Saving

The Watchful Sleep mode, a new ONU power management mode for TDM PONs, which has been published in the paper “Unifying sleep and doze modes for energy-efficient PON systems”, co-authored by Raisa O. C. Hirafuji and Divanilson R. Campelo, has been standardized by the ITU-T in 2014.

Publications Generated in the Master’s Program

- D. A. Khotimsky, D. Zhang, L. Yuan, R. O. C. Hirafuji, and D. R. Campelo, “Unifying sleep and doze modes for energy-efficient PON systems,” *Communications Letters, IEEE*, v. 18, n. 4, p. 688–691, April 2014.

- R. O. C. Hirafuji, and D. R. Campelo, “Eficiência energética em redes ópticas passivas de próxima geração,” In: *Workshop de Redes de Acesso em Banda Larga (WRA), SBRC* 2014, p.3–12. **(BEST PAPER AWARD)**

- R. O. C. Hirafuji, K. B. Cunha, D. R. Campelo, A. R. Dhaini, and D. A. Khotimsky, “The Watchful Sleep mode: a new standard for energy efficiency in future access networks,” *Submitted to IEEE Communication Magazine*, November 2014.

LIST OF SYMBOLS, NOMENCLATURES E ABBREVIATIONS

η: Energy Saving.

10G-EPON: 10 Gigabit-Ethernet Passive Optical Network

A-PON: Asynchronous Transfer Mode-Passive Optical Network

ALR: Adaptive Link Rate

AON: Active Optical Network

ATM: Asynchronous Transfer Mode

B-PON: Broadband-Passive Optical Network

BIP: Bit Interleaved Parity

BWmap: Bandwidth Map

CDR: Clock/Data Recovery

CE: Coexistence Element

CO: Central Office

DBA: Dynamic Bandwidth Allocation

DBRu: Dynamic Bandwidth Report upstream

DSL: Digital Subscriber Line

DWBA: Dynamic Wavelength and Bandwidth Allocation

E-PON: Ethernet Passive Optical Network

EFM: Ethernet in The First Mile

FEC: Forward Error Correction

FTTB: Fiber To The Building

FTTH: Fiber To The Home

FTTN: Fiber To The Neighborhood

FTTx: Fiber To The x

FWI: Forced Wake-up Indication

G-PON: Gigabit-Capable Passive Optical Network

GEM: Gigabit-Capable Passive Optical Network Encapsulation Method

GTC: G-PON Transmission Convergence

HEC: Hybrid Error Correction

Hlend: Header Length Downstream

ICT: Information and Communication Technologies

IEEE: Institute of Electrical and Electronics Engineers

ITU-T: International Telecommunication Union Standardization Sector

KI: Key Index

LDI: Local Doze Indication

LF: Last Fragment

LPI: Local Low Power Indication

LSI: Local Sleep Indication

LWI: Local Wakeup Indication

MIC: Message Integrity Check

NG-PON: Next-Generation Passive Optical Network

NG-PON2: Next-Generation Passive Optical Network Stage 2

OA: Optical Amplifiers

OAM: Operation, Administration and Maintenance

OAN: Optical Access Network

ODN: Optical Distribution Network

OLT: Optical Line Terminal

OMCI: Optical Network Unit Management and Control Interface

ONT: Optical Network Terminal

ONU: Optical Network Unit

P2MP: Point-to-Multipoint

P2P: Point-to-Point

PLI: Payload Length Indicator

PLOAM: Physical Layer Operation, Administration and Maintenance

PON: Passive Optical Network

PSBd: Downstream Physical Synchronization Block

PSBu: Upstream Physical Synchronization Block

Psync: Physical Synchronization Sequence

ROSA: Receiver Optical Subassembly

RT: Remote Terminal

SA: Sleep Allow

SDU: Service Data Unit

SeqNo: Sequence Number

SFC: Superframe Counter

SG: Study Group

SR: Sleep Request

T-CONT: Transmission Container

TC: Transmission Convergence

TDM-PON: Time Division Multiplexed Passive Optical Network

TDMA: Time Divison Multiplexing Access

TIA: Trans-Impedance Amplifier

TOSA: Transmit Optical Subassembly

TWDM-PON: Time and Wavelength Division Multiplexed Passive Optical Network

VCSEL: Vertical-Cavity Surface-Emitting Lasers

VSSN: Vendor-Specific Serial Number

WDM-PON: Wavelength Division Multiplexed Passive Optical Network

XG-PON: 10-Gigabit-Capable-Passive Optical Network

XGTC: XG-PON Transmission Convergence

Chapter 1 Introdução

1.1 Contextualização

Nos últimos anos, a eficiência energética tem se tornado um fator cada vez mais importante para as redes de comunicação, principalmente por fatores econômicos e ambientais. Estima-se que as Tecnologias de Informação e Comunicação (*Information and Communication Technologies*, ICT) são responsáveis por cerca de 2,6 % do consumo global de energia [1]. A redução consumo de energia traz uma diminuição dos custos operacionais da rede, e, para países com matrizes energéticas primordialmente não-renováveis, traz também uma redução na emissão de CO_2.

Dado o rápido crescimento da demanda por serviços de banda larga, o tráfego IP global mais que quintuplicou entre 2008 e 2013, e é estimado que este tráfego irá triplicar de 2013 até 2018 [2]. Tal crescimento fará com que os provedores de serviço ampliem a capacidade de suas redes, o que aumentará a quantidade de componentes ativos nas redes. Ou seja, caso não haja nenhuma melhoria na eficiência energética destes componentes, estima-se que o consumo de energia nas redes de comunicação aumente significativamente nos próximos anos [3].

Uma rede de telecomunicações de banda larga é composta por: redes de *backbone* (ou núcleo), redes de agregação, e redes de acesso. As redes de acesso, também conhecidas como redes de última milha, compreendem o segmento da rede que conecta os usuários finais, i.e. os clientes, até o Escritório Central (*Central Office*, CO) do provedor de serviço. Essas redes também são referidas como redes de primeira milha, pois são, do ponto de vista do usuário, o primeiro segmento para uma rede maior. Exemplos de redes de acesso incluem: *Digital Subscriber Line* (DSL), que utiliza o par trançado de cobre; *Cable Modem*, que utiliza o cabo coaxial; e WiMax, que utiliza ondas de rádio. A Figura 1.1 (obtida em [4]) mostra uma previsão do consumo de energia em redes de telecomunicações de 2009 até 2017, onde E_0 é o consumo de energia em redes de telecomunicações em 2009. Observe na Figura 1.1 que a maior parte do consumo energético se encontra nas redes de acesso, principalmente por causa do elevado número de componentes ativos [5].

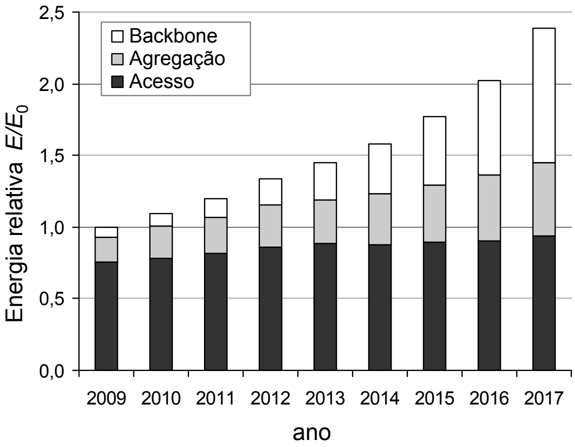
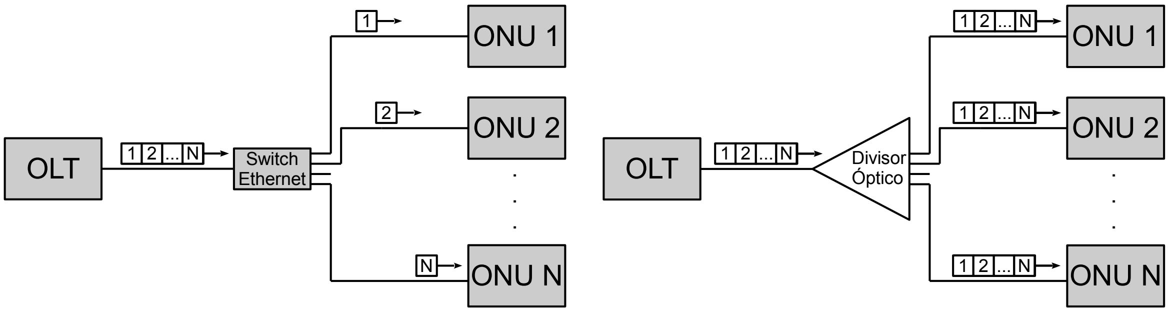


Figure 1.1: Projeção do consumo energético em redes de telecomunicações [4].

Apesar da pesquisa em Redes Ópticas de Acesso (*Optical Access Networks*, OANs) terem começado em meados de 1980, apenas no início deste século que as OANs começaram a se popularizar [6]. Embora o uso de fibra óptica proporcione diversas vantagens em relação aos guias metálicos, como largura de banda bastante superior, baixas perdas de transmissão e ausência de interferência eletromagnética; o custo de componentes ópticos e a falta de aplicações que demandem muita largura de banda teriam sido uma barreira para a disseminação das OANs [7]. Conforme os avanços tecnológicos nas tecnologias ópticas diminuíram o preço dos componentes ópticos, e novos serviços que demandavam muita largura de banda foram surgindo, os provedores de serviço começaram a investir em sistemas *Fiber To The x* (FTTx) [8]. FTTx representa um conjunto tecnologia de acesso óptico, onde o "x" pode ser: "*Home*" (*Fiber To The Home*, FTTH), onde a fibra vai até à casa do usuário; "*Neighborhood*" (*Fiber To The Neighborhood*, FTTN), onde a fibra alcança um vizinhança; "Building" (*Fiber To The Building*, FTTB), onde a fibra chega à base de um prédio; entre outros. Nos dois últimos casos, onde a fibra não chega até seu destino final, a conectividade final pode ser feita por um guia metálico. Portanto, estes sistemas podem ser considerados sistemas híbridos de fibra e par trançado de cobre [6].

No âmbito de FTTx, podem ser encontradas tanto arquiteturas Ponto-a-Ponto (*Point-to-Point*, P2P) quanto arquiteturas Ponto-a-Multiponto (*Point-to-Multipoint*, P2MP). Dependendo do uso de equipamentos ativos ou passivos podemos classificar as OANs como passivas, que seriam as PONs, e ativas, que seriam as Redes Ópticas Ativas (*Active Optical Network*, AON). A Figura 2.2 ilustra esses dois tipos de redes.

Dentre as tecnologias de redes de acesso existentes, tem-se que as redes de acesso por



(a) AON (b) PON

Figure 1.2: Redes Ópticas Ativas e Passivas.

fibra fornecem taxas de bit elevadas com o nível de consumo mais baixo por linha de assinante, como mostrado na Tabela 1.1 [9, 10]. Embora as Redes Ópticas Passivas (*Passive Optical Networks*, PONs) sejam consideradas as redes ópticas de acesso mais energeticamente eficientes para taxas baixas, é necessário reduzir ainda mais o seu consumo energético. As Unidades de Rede Óptica (*Optical Network Units*, ONUs), dispositivos da rede localizados nas proximidades do usuário final, são responsáveis por mais de 65% do consumo de energia em PONs [11]. Grande parte deste consumo de energia poderia ser reduzido, pois mesmo quando a ONU não está transmitindo ou recebendo tráfego, ela continua ativa.

Para ilustrar melhor o problema do consumo de energia nas ONUs, considere que uma ONU com várias portas Ethernet consome cerca de 10 W. Uma lâmpada energeticamente eficiente (por exemplo, uma lâmpada fluorescente compacta) consome cerca de 20 W. Em princípio, parece que a ONU é mais energeticamente eficiente que a lâmpada. Porém, diferentemente da lâmpada, a ONU permanece ligada 24 horas por dia, o que leva a um consumo de energia de 240 Wh/dia. Se considerarmos que a lâmpada fica ligada apenas 6 horas por dia, então o consumo da lâmpada será de 120 Wh/dia. Como resultado, a ONU consume o dobro de energia da lâmpada [12]. Suponha agora um caso hipotético em que há 100 milhões de usuários de PON, o que levaria o consumo de potência a 1 GW. O consumo anual de energia destes usuários seria de cerca de 8,76 TWh. Considerando a taxa de emissão de CO_2 na atmosfera como 0,7 kg/kWh, então a quantidade de CO_2 emitido na atmosfera no final de um ano seria de aproximadamente 6 milhões de toneladas. Com a economia de 1 W por ONU em 1 bilhão de usuários, a construção de duas usinas de energia de 500 MW [13] poderia ser evitada.

Além disso, as redes PONs possuem algumas peculiaridades. Diferentemente de um aparelho de telefone convencional, a ONU não pode ser alimentada pelo *loop* local e

Table 1.1: Consumo de Energia em Redes de Acesso.

			Taxa de acesso por usuário		
			10 Mbps	75 Mbps	1 Gbps
Tecnologia	Consumo de potência total por usuário	Limite da tecnologia	Energia consumida por bit	Energia consumida por bit	Energia consumida por bit
DSL	8 W	15 Mbps	816 nJ/b	NA	NA
PON	7 W	2,4 Gbps	745 nJ/b	99 nJ/b	NA
Fiber To The Node	14 W	50 Mbps	1,42 μJ/b	NA	NA
Rede Óptica de Acesso Ponto-a-Ponto	12 W	1 Gbps	1,2 μJ/b	160 nJ/b	12 nJ/b

depende da bateria local no caso de falta de energia. Porém, protocolos PON ponto-multiponto requerem transmissões *upstream* regularmente que tendem a drenar a bateria mesmo quando não está ocorrendo nenhuma comunicação útil. Portanto, as ONUs de uma PON TDM devem ser energeticamente eficientes, mas elas devem também ser capazes de manter serviços críticos (normalmente de voz) em caso de queda de energia [14].

Para lidar com a tarefa de reduzir o consumo de potência em redes PONs, a recomendação *International Telecommunication Union Standardization Sector* (ITU-T) G.987.3 [15] introduziu dois mecanismos de gerenciamento de potência baseado em protocolo para os sistemas PONs existentes: os modos *Cyclic Sleep* e *Doze*. Em termos gerais, estes dois modos consistem em fazer com que o Terminal de Linha Óptica (*Optical Line Terminal*, OLT) permita que as ONUs alternem entre fases de pleno consumo de potência e fases de economia de potência. Uma vez em uma fase de economia de potência, a ONU alterna entre dois estados: um estado de consumo pleno de potência e um estado de baixo consumo de potência. A diferença entre os dois modos está na semântica dos respectivos estados de baixo consumo de potência.

Contudo, apesar dos modo *Cyclic Sleep* e *Doze* terem sido padronizados pela ITU-T, não há razão técnica para manter a separação entre eles. Recentemente, propusemos um único modo de gerenciamento de potência, chamado de modo *Watchful Sleep*, que unifica os modos *Cyclic Sleep* e *Doze* em um modo único de gerenciamento de potência, reduz o número de mensagens de sinalização trocadas entre a OLT e a ONU e supera os dois modos anteriores em eficiência energética.

1.2 Principal Objetivo Desta Dissertação

O principal objetivo desta dissertação é apresentar e analisar o desempenho do modo *Watchful Sleep*, um novo modo de gerenciamento de potência que foi padronizado pela ITU-T em 2014 [16]. Nós mostramos que o modo *Watchful Sleep* combina as vantagens dos modos *Cyclic Sleep* e *Doze* em um *framework* único e mais simples que supera-os em eficiência energética. Para avaliarmos o desempenho do modo *Watchful Sleep*, um simulador de redes PON orientado a eventos foi desenvolvido utilizando o OMNeT++ durante este trabalho de mestrado.

1.3 Trabalhos Relacionados

À medida que as preocupações com o aquecimento global e com as emissões de CO_2 foi ganhado atenção na última década, vários estudos sobre a pegada energética nas redes de telecomunicações surgiram. Em 2008, foi estimado em [1] que a ICT consome cerca de 2,6% do consumo primário de energia global. Lange *et al.* publicou em 2009 um artigo [4] com uma previsão do consumo energético em redes de telecomunicações, prevendo um crescimento de cerca de 150% de 2009 a 2017. Também em 2009, Baliga *et al.* apresentou em [11] um modelo do consumo de potência em redes IP para estimar o consumo de potência da Internet, e comparou o consumo de potência de várias técnologias de rede de acesso. O consumo estimado por este modelo foi de 0,4% do consumo de energia elétrica em países com Internet banda larga. Nos anos seguintes, Lange *et al.* e Baliga *et al.* publicaram alguns artigos sobre o consumo de potência em redes de telecomunicações e propuseram algumas soluções para resolver o problema do consumo de potência [3, 5, 10].

Estes números fizeram com que a indústria e a academia colaborassem em busca de soluções para o aumento contínuo do consumo de energia em redes de telecomunicações. Em 2009, a ITU-T publicou um documento sobre conservação de potência em redes G-PON [17], descrevendo mecanismos de gerenciamento de potência em ONUs, tais como *Power Shedding*, modo *Sleep* e modo *Doze*. Existem vários estudos na literatura que discutem os impactos do modo *Sleep* em ONUs, tais como [18, 19, 20]. Apenas em 2010 que a ITU-T publicou a recomendação ITU-T G.987.3 com os modos *Cyclic Sleep* e *Doze*. Em [21], Björn Skubic e Dave Hood apresentam resultados de simulação dos modos *Cyclic Sleep* e *Doze*, mostrando que o modo *Cyclic Sleep* pode economizar mais de 60% de energia para uma baixa intensidade de tráfego.

Além dos mecanismos mencionados acima, vários outros esquemas de economia de energia estão sendo estudados/desenvolvidos. Por exemplo, em [22], os autores propõem um híbrido de *sleep* a controle de *Adaptive Link Rate* (ALR). Economia de potência com controle de ALR consiste em mudar a taxa do enlace de acordo com a carga de tráfego, assumindo que enlaces com taxas menores consomem menos energia. Nesse artigo, os autores utilizaram o mecanismo proposto em um sistema 10 Gigabit-Ethernet Passive Optical Network (10G-EPON) e mostraram que o mecanismo híbrido é mais energética mente eficiente que o modo *sleep* ou o controle de ALR isolados.

1.4 Apresentação do manuscrito

O resto desde trabalho está organizado da seguinte forma. O capítulo 3 apresenta o básico de PONs necessário para o entendimento de esquemas de gerenciamento de potência que serão apresentados nos capítulos seguintes. O Capítulo 4 discute eficiência energética em sistemas PON e algumas técnicas de gerenciamento de potência, tais como os modos *Cyclic Sleep* e *Doze*. O Capítulo 5 descreve o modo *Watchful Sleep*, que é a principal contribuição deste trabalho. O Capítulo 6 apresenta e discute a avaliação de desempenho do modo *Watchful Sleep* e sua comparação com os outros modos padronizados pela ITU-T. Finalmente, o Capítulo 7 apresenta de forma sucinta as principais descobertas e conclusões deste trabalho.

Chapter 2 Introduction

2.1 Contextualization of the topic

Energy efficiency in telecommunication networks has gained momentum in recent years, mainly due to economical and environmental issues. It has been estimated that Information and Communication Technologies (ICT) are responsible for approximately 2.6 % of the global energy consumption [1]. A reduction in the power consumption of ICT equipment potentially decreases the network operational costs and, for those countries whose main energy matrix is non-renewable, the CO_2 emissions as well.

Due to the continuously increasing demand for broadband, the global IP traffic has increased more than five times from 2008 to 2013, and it is estimated that this traffic will have a threefold increase from 2013 to 2018 [2]. Such a growth will stimulate service providers to enhance their network capacity, which will lead to an increase in the number of active devices and in the energy consumption of the network. Thus, if no course of action is taken to improve the energy efficiency of these devices, it is expected that the energy consumption of telecommunication networks will significantly grow in the next few years [3].

Typically, the structure of a broadband telecommunication network consists of a backbone (or core) network, an aggregation network, and an access network. The access network, also known as the last mile network, comprises the network segment that connects end users, i.e. the subscribers, to the service provider's Central Office (CO). This network is also referred to as the first mile network, because it represents the first network segment from the end user perspective. Examples of access networks include: Digital Subscriber Line (DSL) networks, which are based on twisted copper pair; Cable Modem networks, which are based on coaxial cables; and WiMax networks, which use radio waves. Figure 2.1 (obtained from [4]) shows a forecast of the energy consumption for telecommunication networks from 2009 until 2017, where E_0 is the energy consumption in telecommunication networks in 2009. One can observe in Figure 2.1 that most of the energy is consumed in the access network segment, mainly due to the high number of active devices in the access networks [5].

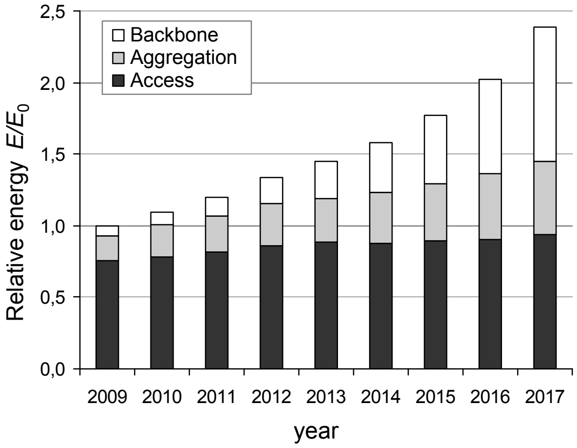
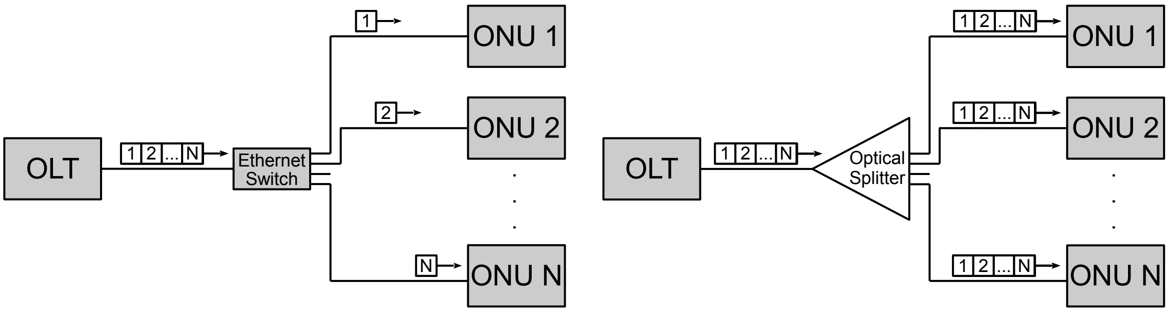


Figure 2.1: Energy consumption forecast for telecommunication networks [4].

Even though research efforts on Optical Access Networks (OANs) began around mid 1980's, these networks became popular in the beginning of this century only [6]. Although the use of optical fibers brings several advantages over the traditional copper-based access loops, such as a superior bandwidth, a low transmission loss, and the immunity to electrical interference, the high cost of equipment and the lack of killer applications for broadband discouraged the deployment of OANs in a large scale [7]. As the progress in optical technologies brought down component and system costs, and as new bandwidth-hungry applications started to emerge, service providers decided to invest in Fiber to the x (FTTx) systems [8]. FTTx may represent a number of optical access technologies, where the "x" can refer to, for instance: "Home" (Fiber To The Home, FTTH), where the fiber is connected all the way from the service provider to the customer's household; "Neighborhood" (Fiber To The Neighborhood, FTTN), where the fiber is connected to the customer's neighborhood; "Building" (Fiber To The Building, FTTB), where the fiber is connected to a building. In the last two cases, for which the fiber does not reach the final destination, the last segment can be connected through twisted pairs. Therefore, these systems can be considered as hybrid fiber twisted pair systems [6].

Within FTTx networks, there can be Point-to-Point (P2P) or Point-to-Multipoint (P2MP) architectures. Depending on the use of passive or active devices, an FTTx network can be classified as passive, as in Passive Optical Networks (PONs), or as active, as in Active Optical Networks (AONs). Figure 2.2 illustrates these two kinds of networks.

Among the existing access network technologies, the optical access networks are able



(a) AON (b) PON

Figure 2.2: Active and Passive Optical Networks.

to provide a high bit rate with the lowest power consumption per subscriber (see Table 2.1) [9, 10]. Even though PONs are considered as the most energy efficient optical access network technology for low access rates, it is necessary to further reduce their power consumption. The Optical Network Units (ONUs), which are the devices located at the customer premises, are responsible for over 65% of the power consumption in PONs [11]. Part of this power consumption could be reduced, since the ONUs are constantly powered on, even when there is no traffic to send or receive.

To better illustrate the problem of the energy consumption at the ONUs, consider that an ONU with several Ethernet ports consumes around 10 W. An energy efficient light bulb (e.g., a compact fluorescent bulb) consumes approximately 20 W. At first, it seems that the ONU is more energy efficient than the light bulb. However, differently from the light bulb, the ONU remains ON 24 hours a day, which leads to an energy consumption of 240 Wh/day. If we consider that the light bulb is ON only 6 hours a day, then the light bulb consumes 120 Wh/day.As result, the ONU consumes twice as much energy as the light bulb's [12]. Now, suppose a hypothetical case in which there are 100 million PON users, which would lead to a power consumption of 1 GW. The annual energy consumption of these users would be around 8.76 TWh. Considering the CO_2 emission rate in atmosphere as 0.7 kg/kWh, then the amount of CO_2 released to the atmosphere in one year would be approximately 6 million tons. By saving 1 W per ONU in one billion users, one could avoid building two 500-MW power plants [13].

Nevertheless, PONs have some peculiarities. Unlike a conventional telephone network apparatus, the ONU cannot be powered from the local loop and must rely on the local battery backup in case of a power outage. However, PON point-to-multipoint protocols require regular upstream transmissions and tend to drain battery power even when no useful communication is taking place. Therefore, ONUs of TDM PONs should

Table 2.1: Access networks power consumption.

			Per user access rate		
			10 Mb/s	75 Mb/s	1 Gb/s
Technology	Total per user power consumption	Technology Limit	Energy per bit	Energy per bit	Energy per bit
DSL	8 W	15 Mb/s	816 nJ/b	NA	NA
PON	7 W	2.4 Gb/s	745 nJ/b	99 nJ/b	NA
Fiber To The Node	14 W	50 Mb/s	1.42 μJ/b	NA	NA
Point-to-Point Access Optical Network	12 W	1 Gb/s	1.2 μJ/b	160 nJ/b	12 nJ/b

be energy efficient, but they must be able to sustain critical life-line services (usually voice) in case of a power outage [14].

To face the task of reducing the power consumption in PONs, the *International Telecommunication Union Standardization Sector* (ITU-T) G.987.3 standard [15] introduced two protocol-based power management mechanisms for existing ITU-T PON systems: the Cyclic Sleep and Doze modes. These two modes are characterized by the Optical Line Terminal (OLT) allowing the ONU to swap between an active phase and a power saving phase. Once in a power saving phase, the ONU alternates between two states: a full power state and a low power state. The difference between the two modes lies in the semantics of the respective low power states.

However, despite the fact that the Cyclic Sleep and Doze modes have been proposed and standardized by the ITU-T, there is no technical reason to maintain a separation between them. Recently, we proposed a new ONU power management mode, named the Watchful Sleep mode, that unifies both Cyclic Sleep and Doze modes into a single power management mode, reduces the number of signaling messages between the OLT and the ONU and outperforms both previous modes in energy efficiency [23].

2.2 Main Goal of this Dissertation

The main goal of this dissertation is to present and evaluate the performance of the Watchful Sleep mode, a novel ONU power management mode that has been standardized by the ITU-T in 2014 [16]. We show that the Watchful Sleep mode combines the advantages of both Doze and Cyclic Sleep modes into a unique and simpler framework and outperforms them in energy efficiency. In order to evaluate the performance of the Watchful Sleep mode performance, an event-driven PON simulator in OMNeT++ has been developed in this master's work.

2.3 Related Work

As the concerns with the global warming and CO_2 emissions gained attention in the last decade, many studies on the energy footprint telecommunication networks emerged. In 2008, it was estimated in [1] that the ICT consumes around 2.6% of the worldwide primary energy consumption. Lange *et al.* published in 2009 a paper [4] with a forecast of the energy consumption of telecommunication networks, where the energy consumption increased about 150% from 2009 to 2017. Also in 2009, Baliga *et al.* presented in [11] a model of the power consumption in optical IP networks to estimate the energy consumption of the Internet, and compared the power consumption of various access networks technologies. The power consumption estimated through the model was 0.4% of the electricity consumption in broadband-enabled countries. In the subsequent years, Lange *et al.* and Baliga *et al.* published some papers about the power consumption in telecommunication networks, and also proposed some solutions to address the issue [3, 5, 10].

These numbers compelled the industry and the academia to collaborate in order to find solutions for the continuously increasing energy consumption in telecommunication networks. In 2009, the ITU-T published a document on G-PON power conservation [17], describing the power management mechanism in ONUs, such as Power Shedding, Sleep mode and Doze mode. There are many studies in the literature that discussed the impacts of the Sleep mode in ONUs, such as [18, 19, 20]. Only in 2010 that the ITU-T published the ITU-T G.987.3 recommendation with the Cyclic Sleep and Doze modes. In [21], Björn Skubic and Dave Hood present some simulation results on the Cyclic Sleep and Doze modes, showing for the Cyclic Sleep mode over 60% of energy saving for low traffic activity.

Besides the aforementioned mechanisms, many other power saving schemes are being studied/developed. For example, in [22], the authors propose a hybrid sleep and Adaptive Link Rate (ALR) control. Power saving with ALR control consists on changing the link rate according to the traffic load, assuming that lower link rates consumes less energy. In the paper, the authors applied the proposed hybrid mechanism to a 10 Gigabit-Ethernet Passive Optical Network (10G-EPON) system and showed that the hybrid mechanism was more energy efficient than the Sleep mode or the ALR control isolated

2.4 Outline of the Dissertation

The remainder of this dissertation is organized as follows. Chapter 3 presents the basics of PONs necessary for understanding the power management schemes that will be presented in the subsequent chapters. Chapter 4 discusses about energy efficiency in PON systems and some power management techniques, such as the Cyclic Sleep and Doze modes. Chapter 5 describes the Watchful Sleep mode, the main contribution of this work. Chapter 6 presents and discusses the performance evaluation of the Watchful Sleep mode and its comparison with the other standardized modes by ITU-T. Finally, Chapter 7 summarizes the main findings and conclusions of this work.

Chapter 3 Passive Optical Networks

This chapter revisits the main PON standards and architectures necessary for understanding the power saving techniques that will be presented in the subsequent chapters.

3.1 Passive Optical Network

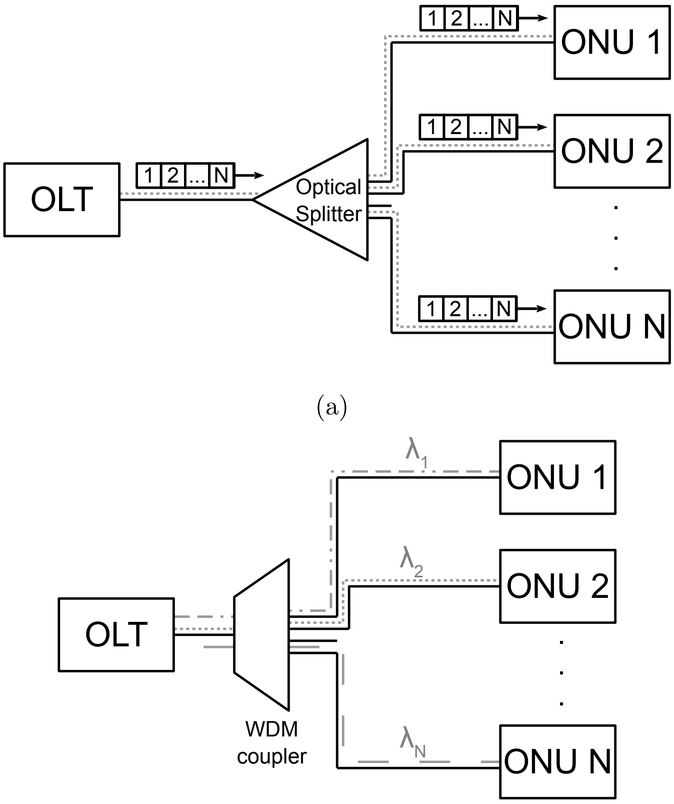
PONs are FTTx networks characterized by the presence of a passive Optical Distribution Network (ODN) and by the P2MP architecture, usually deployed with a tree topology. A PON is formed by an Optical Line Terminal (OLT), located at the Central Office (CO), some ONUs (or Optical Network Terminals, ONT) located at the premises of the end user, and an ODN, which is basically comprised of the optical fibers and the Remote Terminal (RT) that connects the OLT to the ONUs. TDM PONs use a passive splitter as the RT, whereas WDM-PONs use a WDM coupler as the RT. In both TDM and WDM PONs, a single-fiber connection is used for the downstream and upstream directions.

In a TDM PON, downstream and upstream signals are multiplexed through two different wavelengths. The same signal from the OLT is broadcast to every ONU by the splitter. However, in the upstream direction several ONUs are served by only one OLT, so the signals from different ONUs are multiplexed in time domain.

In a WDM PON, each ONU has its own dedicated wavelength for both upstream and downstream signals. Since in a WDM PON each ONU receives its own wavelength, a WDM PON has better privacy and a better scalability. However, with current technology, WDM PONs are still costly to compete with TDM PONs. Figure 3.1 shows the architectures of TDM and WDM PONs.

3.1.1 History of PON standards

The development of PON technology began in the 1980s, however, the PON standardization efforts only began in the 1990s. In 1995 the Full Service Access Network (FSAN)



(a)

(b)

Figure 3.1: Architectures of a) TDM-PON and (b) WDM-PON.

consortium was founded to standardize common requirements and services for a passive optical access network system. The FSAN group gave rise to over ten standards, that were later adopted by the International Telecommunication Union Standardization Sector (ITU-T) [8]. The first PON standard created by the FSAN group was based on Asynchronous Transfer Mode (ATM), and, because of that, it was originally called A-PON. The A-PON standard was adopted by the ITU-T and developed into a recommendation that eventually became the ITU-T G.983.1. Later, the A-PON system evolved to the Broadband PON (B-PON), and was later adopted by the ITU-T as an addition to the ITU-T G.983 series. These standards specified 622 Mbps downstream, and 155 Mbps or 622 Mbps aggregated upstream data rates. Each OLT could be shared by up to 32 ONUs for a maximum separation of 20 km between the OLT and the ONU. B-PONs still use ATM cell for data framing [8].

Around the turn of the millennium, new applications that required more bandwidth started to emerge, and the downstream rate of 622 Mbps distributed across 32 subscribers was not enough anymore. Thus, a new generation of PON became necessary.

In 2001, the Institute of Electrical and Electronics Engineers (IEEE) 802.3 began the project 802.3ah – Ethernet in The First Mile (EFM), whose purpose was to standardize the transport of Ethernet frames on PONs. The IEEE 802.3ah E-PON standard was ratified in June 2004, and it specifies a symmetric upstream/downstream line rate of 1 Gb/s and a transmission distance of 20 km with 16 ONUs per OLT. This standard became very popular in East Asia countries, especially in Japan and Korea.

Simultaneously to the development of the E-PON standard, the ITU-T Study Group (SG) 15 was working on a new PON standard. In 2003 the first G-PON standard, ITU-T G.984 series, was published [13]. It specified a 2.48832 Gb/s downstream, and 1.24416 Gb/s or 2.48832 Gb/s upstream data rate. The G-PON standard introduced a new framing mechanism called G-PON encapsulation method (GEM). Although the standard was published in 2003, G-PON systems only began to be deployed in substantial volume around 2008–2009 [13].

In 2007, discussions on the next-generation of PONs, the NG-PONs, had an start. In that year, the IEEE 802.3av task force was stabilized in order to develop 10 Gb/s E-PON systems [8], and the FSAN group also launched a white paper project to define the NG-PONs requisites. The FSAN only completed this white paper in mid-2009 [13]. The 10 Gigabit-EPON (10G-EPON) standard was established in 2009 by the IEEE 802.3av task force. The 10GE-PON may have asymmetric data rates of 10 Gb/s downstream and 1 Gb/s upstream, or symmetric data rates of 10 Gb/s downstream/upstream. In 2010 the ITU-T published the 10-Gigabit-Capable-PON (XG-PON[1]) standards, the ITU-T G.987 series. The XG-PON1 has a data rate of 9.95328 Gb/s downstream and 2.48832 Gb/s upstream, whereas the XG-PON2 has a symmetric data rate of 9.95328 Gb/s downstream/upstream. For the sake of simplicity, data rates of 1.24416 Gb/s, 2.48832 Gb/s and 9.95328 Gb/s will be simply referred as 1.25 Gb/s, 2.5 Gb/s and 10 Gb/s, respectively.

In 2011, the FSAN group initiated the NG-PON2 project. The major requirements for NG-PON2 are:

1. At least 40 Gb/s aggregate rate in downstream or upstream;
2. A minimum reach of 40 km;
3. A split ratio of 1:64;

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[1] The X is the Roman numeral 10, denoting the nominal 10 Gb/s downstream rate

4. A differential reach of 40 km ;
5. At least 1 Gb/s access rate per ONU [24].

The TWDM-PON fulfils all the requirements, and has a great support from global vendors since most of the TWDM-PON components are already commercially available, as the only significantly new components in TWDM-PON are the tunable receiver and tunable transmitter at the ONU [25]. Therefore, in April 2013, the FSAN group selected TWDM-PON as the primary solution to NG-PON2 [24].

3.1.2 G-PON/XG-PON

The G-PON standard was developed by the ITU-T Study Group (SG) 15 in 2003, and it is defined in the ITU-T G.984 series. Early versions of the ITU-T G.984 series supported ATM framing, just like A-PON/B-PON systems, however, ATM was subsequently deprecated as a fading legacy technology. Nowadays, the ITU-T G.984 supports only one form of payload transport, the GEM, which is usually used to encapsulate Ethernet frames.

A huge improvement G-PON has from its predecessor, the B-PONs, is the possibility of incremental upgrades of already deployed installations, i.e. G-PONs can coexist with other systems in a same ODN in different wavelengths. It is impossible for the B-PONs to coexist with G-PONs on the same optical network, whereas it is possible for the G-PON and XG-PON to coexist within the same optical network since they use distinct wavelengths, as shown in Table 3.1. Observe in Table 3.1 that, even though E-PON and 10G-EPON utilize different wavelengths, they cannot coexist in the same ODN as G-PON and XG-PON do. The E-PON upstream tolerance of ± 50 *nm* (1260-1360 *nm*) overlaps with the 1270 *nm* spectrum assigned to the 10 Gb/s downstream. The upstream coexistence between E-PON and 10G-EPON are done via TDMA, which makes difficult the migration from E-PON to 10G-EPON [13].

3.1.2.1 G-PON/XG-PON Transmission Convergence Layer

The Transmission Convergence (TC) layer is essential for the G-PON family, being responsible for providing transport multiplexing between the OLT and ONUs. It is also responsible for:

Table 3.1: PON Rates and Wavelengths

	G-PON Family		E-PON Family	
	G-PON	XG-PON	E-PON	10G-EPON
Downstream				
Rate [Gb/s]	2.5	10	1	10
Wavelength [nm]	1490	1577	1490	1577
Tolerance [nm]	± 10	-2, +3	±10	-2, +3
Upstream				
Rate [Gb/s]	1.25	2.5	1	1, 10
Wavelength [nm]	1310	1270	1310	1310, 1270
Tolerance [nm]	± 20	± 10	± 50	± 50, ± 10

- ONU discovery, activation, and delay compensation;
- Physical layer Operation, Administration and Maintenance (PLOAM) messages;
- Dynamic Bandwidth Allocation (DBA);
- Mapping for the ONU Management and Configuration Interface (OMCI);
- Forward Error Correction (FEC)[2];
- Power management.

In this section, only a few aspects of the XG-PON Trsnamission Convergence (XGTC) layer will be discussed. For a complete guide on the XGTC layer, one should refer to [15, 13].

Framing

In a TDM-PON, the OLT continuously broadcasts the downstream traffic to the ONUs, and each ONU identifies its own traffic. The downstream physical layer (PHY) frame has a fixed length of 125 μs, and there are no interruptions between these frames. The PHY frame exceeds the XGTC frame, as shown in Figure 3.2. The XGTC frame has an extra header, called Downstream Physical Synchronization Block (PSBd), and a payload with the downstream XGTC frame scrambled and with FEC parity bytes.

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[2] FEC is optional for G-PONs, and always supported in XG-PONs

The frame is scrambled to reduce the likelihood of long sequences of 0s and 1s. The FEC, in XG-PONs, wastes about 13% of the PON capacity.

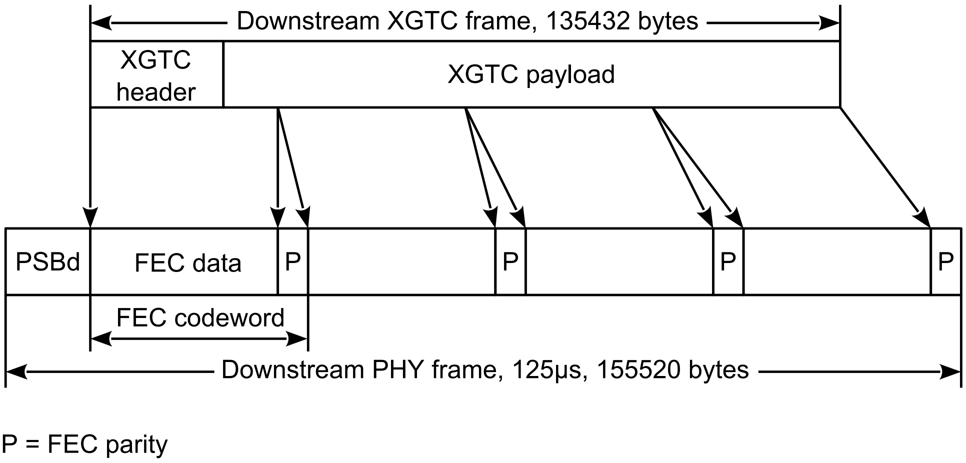

Figure 3.2: XGTC *downstream* PHY frame.

The PSBd is formed by three separate 8-bytes structures:

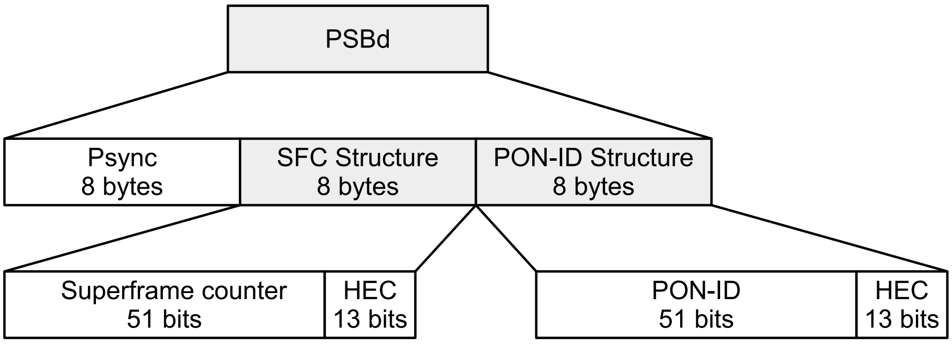

Figure 3.3: Downstream Physical Synchronization Block (PSBd) Structure.

- Physical Synchronization Sequence (PSync): PSync is a fixed sequence of 64 bits. The ONU uses this sequence in order to achieve alignment at the downstream PHY frame boundary;

- Superframe Counter (SFC) Structure: The SFC structure contains a 51-bit SFC (that actually counts frames) and a 13-bit Hybrid Error Correction (HEC) field. For each downstream PHY frame, the SFC value is incremented by one, going back to 0 whenever it reaches the maximum value;

- PON-ID Structure: The PON-ID structure contains a 51-bit PON identifier, called PON-ID, and a 13-bit HEC field.

In the upstream direction, each ONU transmits bursts of traffic inside a time interval controlled by the OLT via the Bandwidth Map (BWmap). The upstream PHY frame also has a duration of $125\mu s$, however, the only purpose of its boundary points is to provide a common time reference shared by the OLT and the ONUs. Differently from the downstream boundary points, that indicate where the PSBd starts, the upstream boundary points do not indicate any specific event. In other words, there is no physically observable 125 μs frame in the upstream direction. The only purpose of the fixed length of 125 μs upstream PHY frame concept is to mark reference points [13]. The upstream PHY burst consists of an Upstream Physical Synchronization Block (PSBu) and a payload with the upstream XGTC bursts, whose content is scrambled and may be protected by FEC. The PSBu contains a preamble and a delimiter (see Figure 3.4).

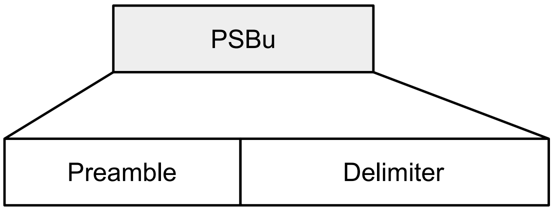

Figure 3.4: Upstream Physical Synchronization Block (PSBu) Structure.

XGEM Frames

In a XG-PON system, the Service Data Units (SDUs), which include user data frames and OMCI management messages, must be encapsulated in XGEM frames, or GEM frames in case of G-PON, to be transported over the PON. The payload of a downstream XGTC frame and the payload of an upstream XGTC burst is formed by one or more XGEM frames. Figure 3.5 shows the structure of a XGEM frame.

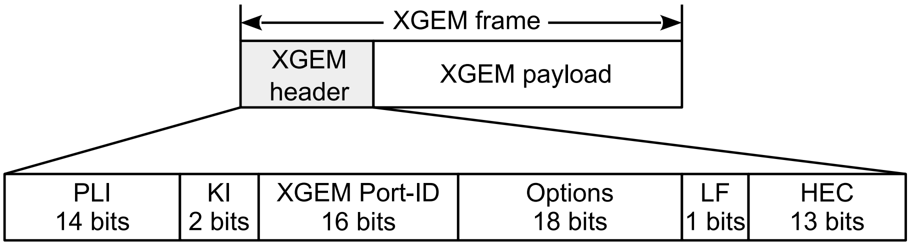

Figure 3.5: XGEM Frame Structure.

The XGEM frame header is formed by the following fields:

- Payload Length Indicator (PLI): The PLI is a field that contains the payload length in bytes. The maximum length of an XGEM frame is 16383 bytes (for a G-PON, the maximum length of a GEM frame is 4095 bytes). The payload length in a XGEM frame is always a multiple of 4, so if the actual payload is not divisible by 4, the frame will be padded with bytes of value 0x55 (which in binary is 0101 0101) until its length is a multiple 4 and longer than the minimum required length of 8 bytes. The GEM frame does not require the length of a GEM frame to be a multiple of 4, thus the GEM frame ends after exactly PLI bytes of payload.

- Key Index (KI): The KI field is an XGEM exclusive field, i.e. it is not in the GEM header. It specifies which data encryption key is being used to encrypt the XGEM payload. A KI value of 00 indicates that the payload is not encrypted, a KI value of 01 and 10 chose one of two possible keys, and the KI value of 11 is reserved for future use. If the KI points to an invalid key or a reserved value, then the XGEM payload is discarded.

- XGEM port-ID: The XGEM port-ID field identifies to which XGEM port the frame belongs.

- Options: The options field is an XGEM exclusive field. This field is currently not in use. According to the ITU-T G.987.3 [15] the use of this field remains for further study.

- Last Fragment (LF): The LF field is an XGEM exclusive field. This field only has 1 bit that signalizes the last SDU fragment. If the LF is 0, then this XGEM is not the last fragment. In this case, it is necessary to keep the XGEM frames until the arrival of the last fragment. If LF is 1, then this XGEM either contains an entire SDU or is the last fragment of an entire SDU. The GEM header has another field to identify the last fragment, the Payload Type Indicator (PTI) field.

- HEC: The HEC field is responsible for the XGEM header error detection and correction.

Fragmentation

If, during the encapsulation of as SDU into a XGEM frame, the SDU is bigger than the desired size, it is possible to break the SDU in two or more fragments (see Figure 3.6).

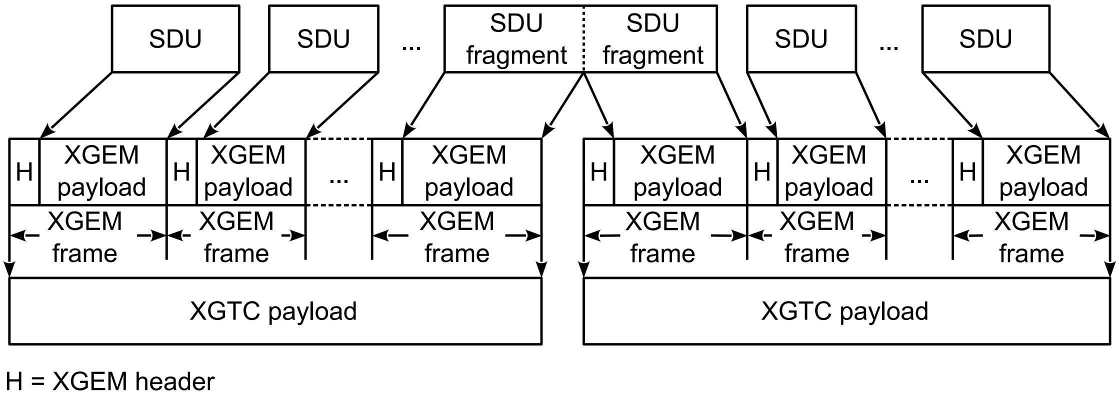

Figure 3.6: SDU Fragmentation in XGEM frames.

There are some rules when fragmenting an SDU. If the available space in the XGTC payload of the current XGTC frame is at least 16 bytes, and the length of the SDU (plus 8 bytes for the XGEM header) is bigger than the available space, then the SDU will be fragmented in two smaller fragments. The first fragment will fill all the available space in the current XGTC frame, and will be marked as not being the last fragment. The second fragment will be encapsulated in the next XGTC frame, and if it fits in the next XGTC frame it will be marked as the last fragment. Otherwise, it will be fragmented again, until the last fragment fits into an XGTC frame. After the first fragment is transmitted, all the remaining fragments must be transmitted before any other XGEM frame. If the available space is smaller than 16 bytes, the rest of the XGTC payload will be filled with 0s.

Another case when the XGEM is fragmented is when the SDU is bigger than the maximum permitted size for the XGEM frame (16383 for XG-PONS and 4095 for G-PONs). Then, even if there is enough space in the current XGTC frame, the SDU will be fragmented according to the aforementioned method.

Downstream Framing

The downstream XGTC frame is formed by a payload and a header (see Figure 3.7). The downstream XGTC frame header has the following fields:

- Header Length Downstream (HLend): The HLend indicates the length of the other field in the header. It has 3 sub-fields: BWmap Length, PLOAM count and HEC. The BWmap Length indicates how many allocation structures there are in the BWmap. The BWmap can only have up to 512, even though this field

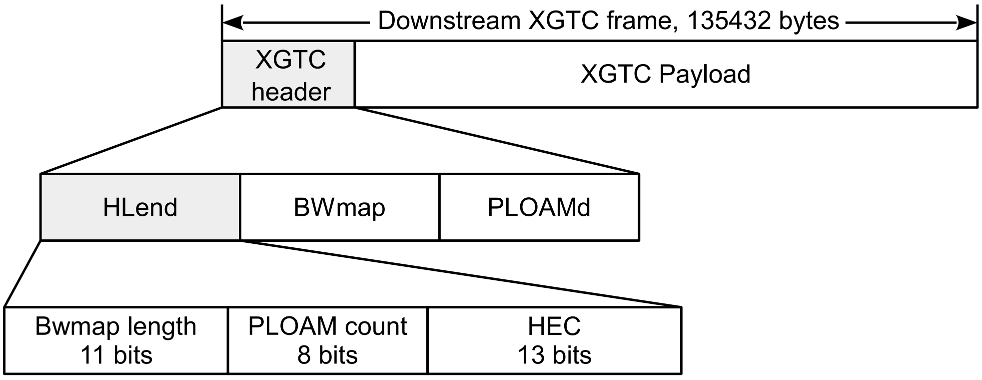

Figure 3.7: Downstream XGTC Frame.

has 11 bits and could support bigger values. The PLOAM count field indicates how many messages there are in the PLOAMd field partition. The HEC protects the HLend field from bit errors.

- BWmap: Specifies when and for how long the ONUs can transmit traffic (See section 3.1.2.1).
- PLOAMd: The PLOAMd field is used for the communication of PLOAM messages with the ONUs. This field can carry a minimum of 0 PLOAM messages, and a maximum of 1 PLOAM message in broadcast (for every ONU) plus one individual PLOAM message for every ONU, or a total of 255 PLOAM messages due to the size of the PLOAM count field (8 bits). Each PLOAM message is 48 bytes long.

BWmap

In every downstream XGTC frame, the OLT authorizes 0 or more ONUs to transmit traffic in the upstream direction through the BWmap. The BWmap is formed by allocation structures (see Figure 3.8) and each allocation structure is formed by the following fields:

- Allocation Identifier (Alloc-ID): The Alloc-ID field is a 14-bit number that indicates the recipient of the bandwidth allocation, such as a Transmission Container (T-CONT). The T-CONT is the recipient of the bandwidth allocation inside the ONU[3].

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[3] Even though each ONU can have more than 1 T-CONT, currently the simulator supports only 1 T-CONT per ONU.

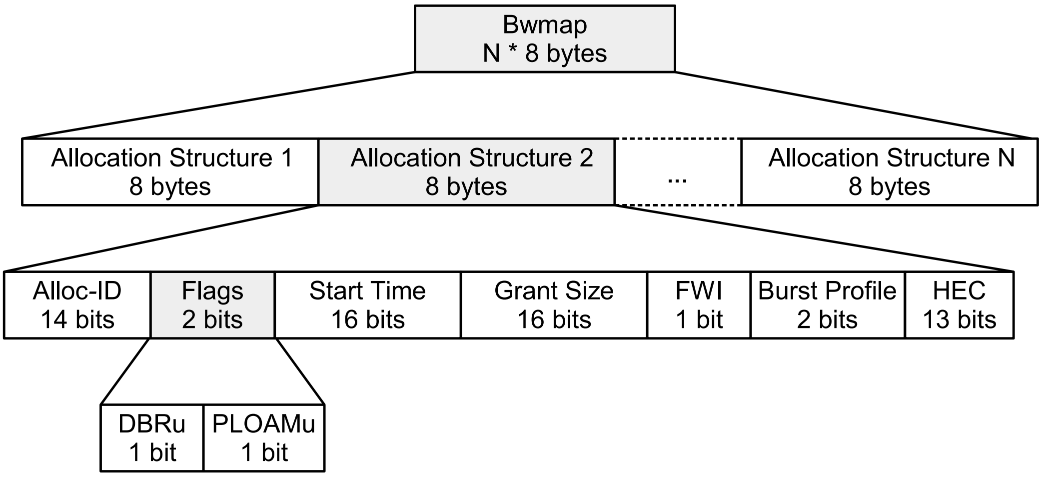

Figure 3.8: Bandwidth Map (BWmap).

- Flags: The Flags field has two separated 1-bit indicator:
  - Dynamic Bandwidth Report upstream (DBRu): If this bit is set, the ONU should send a queue occupancy report, the DBRu, for the given Alloc-ID. Otherwise, the ONU will not send the DBRu.
  - PLOAMu: If this bit is set in the first allocation structure of a burst series, the size of the upstream XGTC burst header should be 52 bytes, and the ONU should transmit a PLOAM message as a part of the XGTC burst header. Otherwise, the upstream XGTC header should have 4 bytes. For all the other allocation structures inside the same burst, this field must be 0.
- Start Time: The Start Time field specifies the start time of the upstream transmission.
- Grant Size: The Grant Size field specifies the XGTC payload length, including the DBRu.
- Forced Wake-up Indication (FWI): If the ONU supports a protocol-based power management mechanism, the OLT sets this bit in order to wake-up an ONU in a power saving state.
- Burst Profile: The Burst Profile field specifies the upstream XGTC burst header. The OLT defines one or more burst profiles and send them to the ONUs via Profile PLOAM messages. This field specifies which burst profile the ONU must use in the upstream response[4].

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[4] The simulator didn't implement any burst profile. Therefore this field is not used during the simulations.

- HEC: The HEC field is responsible for error detection and correction.

Upstream Framing

The upstream XGTC frame is formed by a series of bursts from one or more ONU. Each burst starts with an XGTC header followed by one or more allocations (see Figure 3.9). Each allocation has a DBRu, if it was requested by the OLT, and a series of XGEM frames. The burst header is formed by the following fields:

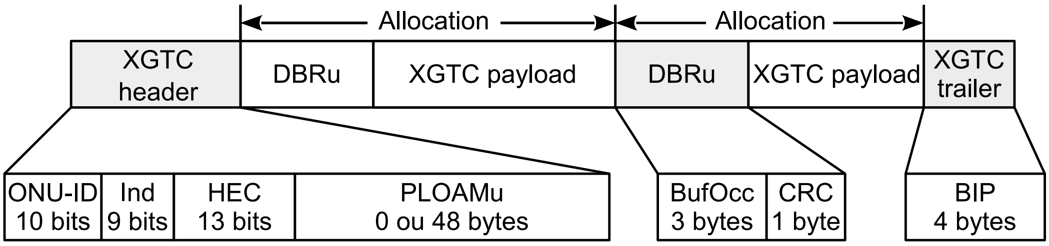

Figure 3.9: *Upstream* XGTC Frame.

- ONU-ID: The ONU-ID field is a 10-bit value that identifies the ONU.
- Ind: The Ind field indicates the ONU status. When the most significant bit (bit 8) is set, it means there are pending upstream PLOAM messages to be sent. When the least significant bit (bit 0) is set, it means that the ONU will not be able to respond to the OLT's allocations. All the other bits in this field are reserved.
- HEC: The HEC field is responsible for error detection and correction.
- PLOAMu: The PLOAMu field may be empty, or may contain a PLOAM message.
- DBRu: The DBRu has 2 sub-fields: The Buffer Occupancy (BuffOcc) and the CRC. The BuffOcc is a 3-bytes sub-field that contains the queue occupancy in this T-CONT. The CRC is responsible for error detection and correction.

At the end of the upstream XGTC burst there is the XGTC trailer, which contains a 4-byte wide Bit Interleaved Parity (BIP) field computed over the entire XGTC burst.

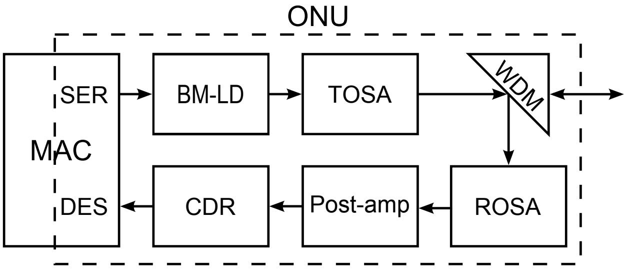

Figure 3.10: Functional building blocks of an ONU.

3.1.3 Functional Building Blocks of an ONU

In a TDM-PON system, the ONU is formed by the transceivers and some components that implements the TC layer functions, as shown in Figure 3.10.

The ONU transmitter consists of a Burst-Mode Laser Driver (BM-LD), and a Transmit Optical Subassembly (TOSA), which contains the laser diode. The ONU receiver consists of a Clock/Data Recovery (CDR) unit, a limiting amplifier (post-amp) and a Receiver Optical Subassembly (ROSA), which includes the photodetector and Trans-Impedance Amplifier (TIA). The transmitter and receiver sections are combined onto a single optical fiber by a WDM coupler. Besides the transmitter and receiver, a very important functional block is the Serializer-Deserializer (SERDES) block, that converts serial to parallel signals and vice versa. In both G-PON and E-PON systems, the CDR and SERDES consume more than 80% of the power of the ONU receiver [26].

In chapters 4 and 5, where we explore some energy management mechanism, we often say that the ONU turns off its transmitter/receiver. By that, we actually mean that the ONU shuts off the transmitter/receiver and its associate circuitry.

3.1.4 TWDM-PON

Figure 3.11 shows a basic architecture for TWDM-PONs, formed by an OLT with four receivers and four transmitters, a passive optical splitter and some colorless ONUs, i.e. ONUs capable of receiving and transmitting in any one of the available wavelengths because of its tunable receiver and transmitter. TWDM-PON increases its data rate by stacking XG-PON via multiple pairs of wavelengths. For instance, the TWDM-PON shown in Figure 3.11 stacks four XG-PONs in four wavelength pairs, λ_{d1} and λ_{u1}, λ_{d2}

and λ_{u2}, λ_{d3} and λ_{u3}, and λ_{d4} and λ_{u4}[5].

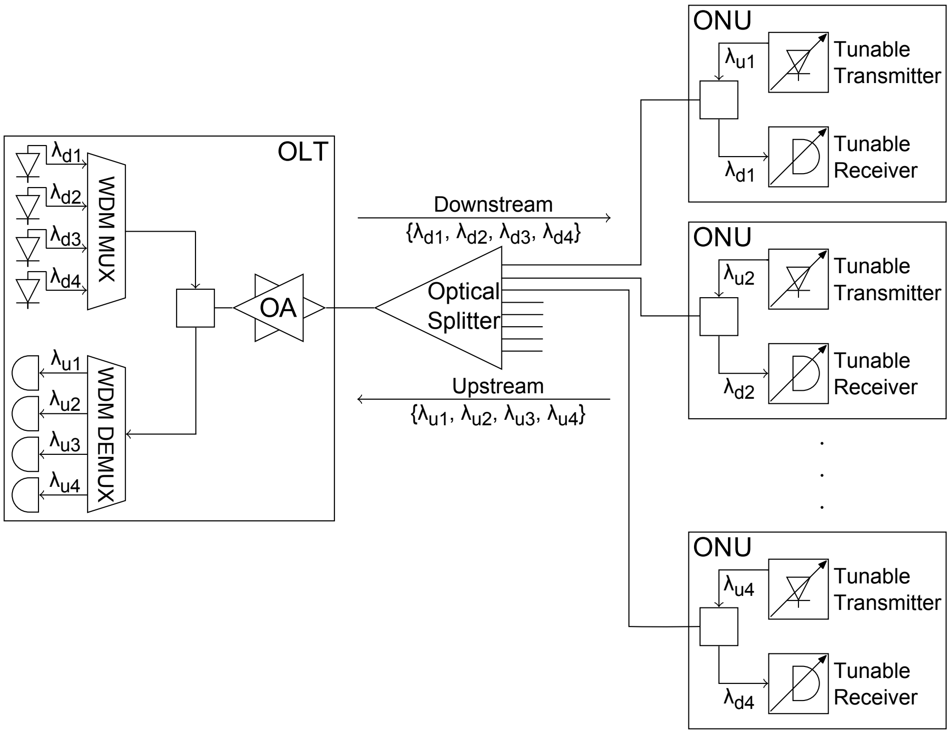

Figure 3.11: Basic architecture for a TWM-PON with four wavelength pairs.

A TWDM-PON with four wavelength pairs is able to provide a nominal rate of 40 Gb/s in downstream and 10 Gb/s in upstream by stacking four XG-PONs. Therefore, each ONU is able to provide peak rates up to 10 Gb/s downstream and 2.5 Gb/s upstream [27]. In order to compensate for high optical losses from increased system reach and split ratios, optical amplifiers (OA) can be deployed at the OLT to optically amplify both upstream and downstream signals. The ODN remains passive, since the OA is placed at the OLT side [24].

To facilitate a smooth migration from legacy PON system[6] to TWDM-PON systems, the TWDM-PON components should be compatible with legacy ODNs and capable of coexisting with legacy PON systems [28]. The coexistence allows some subscribers of an already existing PON system to be moved over to the TWDM-PON system, while maintaining the subscribers that does not want the upgrade in the legacy PON. The TWDM-PON system can be deployed starting with a single wavelength pair, and then it can be upgraded on-demand by adding new wavelength pairs. Figure 3.12 shows a coexistence scenario in the same ODN. The Coexistence Element, (CE) in Figure 3.12,

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[5] The subscript $_{d}$ refers to a downstream wavelength, and the subscript $_{u}$ refers to an upstream wavelength

[6] Legacy PON systems include G-PON, XG-PON1, GE-PON and 10G-EPON.

is a wavelength-selective device used to multiplex the OLT ports onto a single fiber.

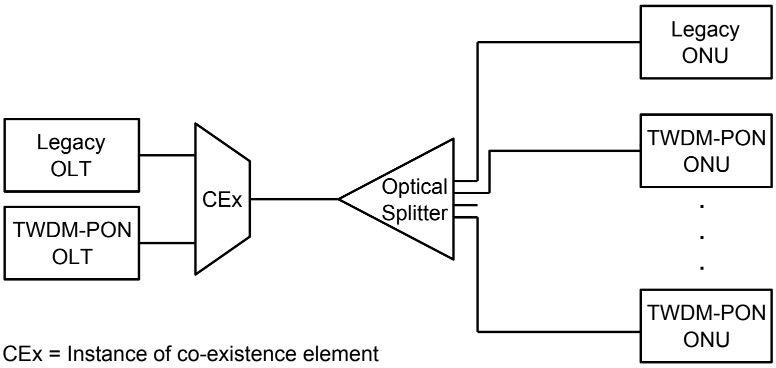

Figure 3.12: TWDM-PON co-existence with legacy PON in the same ODN.

There are several wavelength plans that enable the coexistence of TWDM-PON with a legacy PON. In [24] the authors propose three possible wavelength plans. The first option (Figure 3.13(a)), involves reusing the XG-PON wavelength plans, allowing co-existence with G-PON and Radio Frequency (RF) video overlay [7], but blocking the coexistence with XG-PON. The second option (Figure 3.13(b)) is to redefine the C-band enhancement band to contain both the upstream and downstream wavelengths, which will allow coexistence with G-PON and XG-PON, blocking, however, the coexistence with the RF Video overlay channel. The third plan (Figure 3.13(c)) mixes the other two plans: the TWDM-PON downstream channels are designed in the L-minus band; and the TWDM-PON upstream channels are located in the C-minus band. This plan allows coexistence with G-PON and RF video overlay, but blocks XG-PON.

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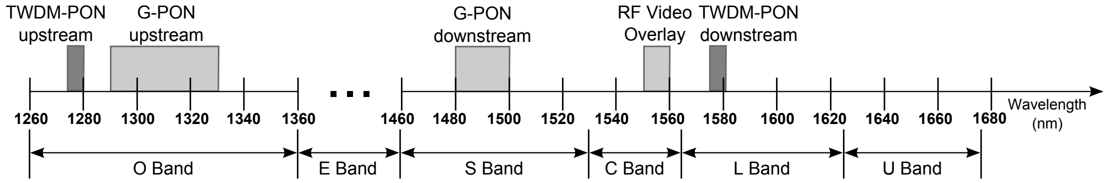
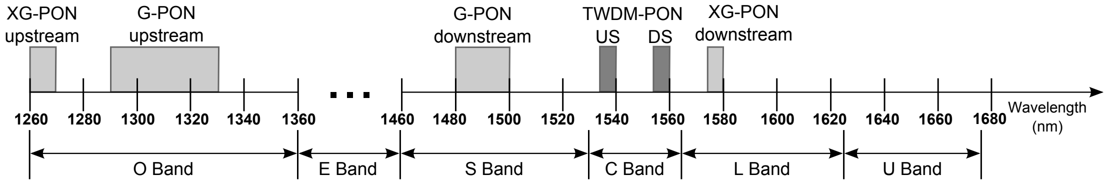
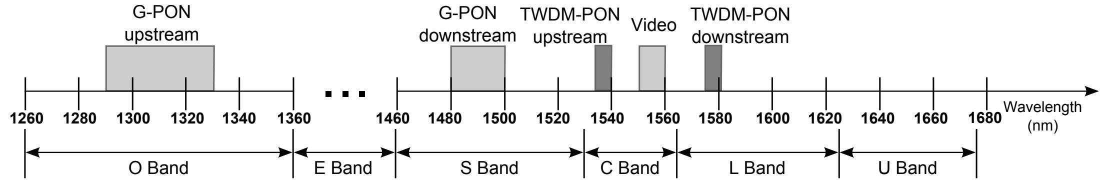
[7] RF Video Overlay is a technology for video transmission in the downstream in a wavelength band between 1550 nm and 1560 nm.



(a) XG-PON wavelength reuse



(b) C-band wavelength plan



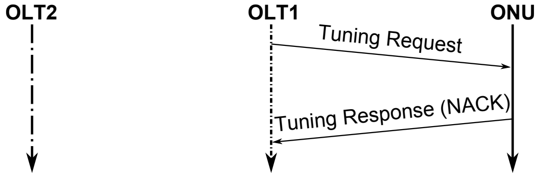
(c) C-minus/L-minus band wavelength plan

Figure 3.13: Wavelenth Plans for TWDM-PON systems [24].

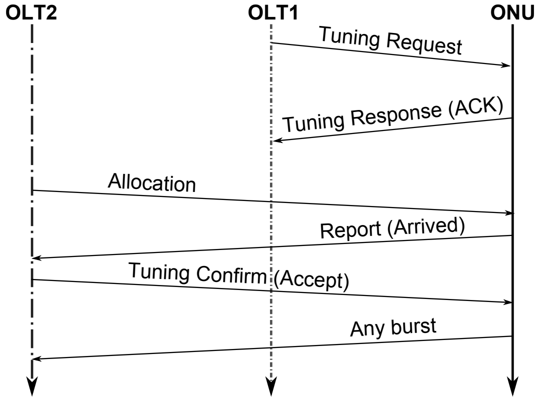
3.2 ONU Migration in TWDM-PON

A TWDM-PON system, differently from G-PON and XG-PON systems, supports multiple wavelength pairs for downstream and upstream transmissions. Therefore, TWDM-PON systems need an ONU migration mechanism, in order to effectively manage the multiple ONUs in multiple wavelength pairs, and to support future Dynamic Wavelength and Bandwidth Allocation (DWBA) schemes. The developed simulator in this master's work supports the ONU migration mechanism, however, it still does not have any DWBA scheme implemented yet. In the beginning of every simulation, all the ONUs are located in the same wavelength pair, and then equally divided between the existing wavelength pairs. This entire section was based on some early drafts of the ITU-T Recommendation G.989, so some terms may change in the final version of the recommendation.

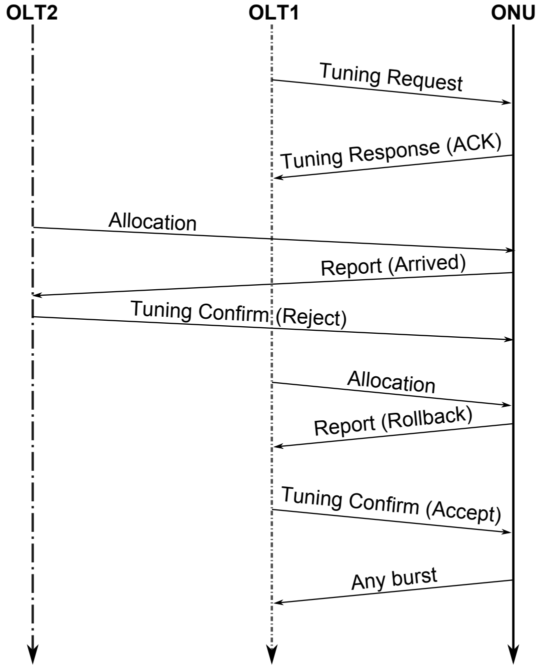
The ONU migration process can be separated into two handshakes: the first one is the OLT sending the tuning command through the source wavelength pair and receiving acknowledgement; the second one is the ONU sending either the tuning confirmation through the target wavelength pair, or the rollback report through the source wavelength pair since the ONU was denied in the target wavelength. Figure 3.14 illustrates the ONU migration process.



(a) Rejected tuning request



(b) Successful wavelength channel tuning



(c) Failed wavelength channel tuning

Figure 3.14: Signalling exchange for the wavelength channel tuning.

When the ONU receives from the OLT a tuning request, the ONU may respond with either ACK or NACK. The ACK response is sent when the ONU is executing the request, whereas the NACK response is sent if the ONU is unable to execute the tuning request. When sending the NACK response, the ONU justifies the NACK response with one of four possible reasons: 1) the ONU is not ready yet; 2) the target wavelength channel is out of the transmitter tuning range; 3) the target wavelength channel is out of the receiver tuning range; 4) the target wavelength channel is out of the transmitter and receiver tuning range. Depending on the reason, the OLT may take further action. If the OLT receives an ACK response, then the OLT source channel informs the OLT target channel about the tuning transaction. Then, both channels send allocations to the ONU to report the tuning result. After the ONU finishes the tuning procedure, it will either report to the target channel with an arrived report that the ONU arrived the target channel, if the tuning was successful (see Figure 3.14(b)), or report to the source channel with a rollback report that the tuning failed (see Figure 3.14(c)). When the OLT target channel receives an arrived report, it sends a tuning confirm accepting the ONU if the ONU is valid, or it can send a tuning confirm rejecting the ONU if the ONU is not valid. If the ONU receives a tuning confirm rejecting the ONU, the ONU will send a rollback report to the source channel.

Chapter 4 Energy Efficiency in PONs

This chapter presents some energy saving mechanisms for PON systems, including the ITU-T standardized Cyclic Sleep and Doze power management modes.

4.1 Energy Saving Techniques

As described in Chapter 3, the basic architecture of a PON consists of an OLT at the CO, some ONUs at the premises of the end user and a passive ODN connecting the OLT to the ONUs. The OLT and the ONU are the only active equipment in a PON.

There are many different ways to categorize energy saving techniques in a PON. In [26], the energy saving techniques are classified as Physical Layer solutions, which target on modifying the physical layer of a PON without modifying the upper layers protocols; Data Link solutions, that target on the TC layer for the GPON family; and Hybrid solutions, that combine physical and data link solutions. In [29], the energy saving techniques are classified as hardware- or software-based techniques.

In this work we will categorize the energy saving techniques with the same approach used in [23], where we considered that the energy efficiency in PONs could be achieved through improvements in components and module designs, one-sided power management techniques (i.e. either at the OLT or ONU), and protocol-based power management techniques. This approach was chosen because it sets a clear distinction regarding complexity between power management techniques. For example, Power Shedding (hereafter explained) is usually grouped together with the Cyclic Sleep and Doze modes, even though the implementation of these modes is much more complex than that of power shedding.

Improvements in components and module designs can enhance the PON energy efficiency regardless of the PON power management capabilities, i.e. it can improve the energy saving achieved through power management techniques, but it can also reduce the power consumption without any power management technique. An example of improvement in components and module designs is the use of Vertical-Cavity Surface-Emitting Lasers (VCSELs)-based ONUs, which can minimize the power consumed in both active and power management modes [30, 31]. The VCSEL-ONUs can be deployed in legacy PON and in future NG-PON2 systems, such as TWDM-PONs [32].

One-sided power management techniques are specific to either the OLT or ONU, thus they do not involve signalling between them. An example of an ONU-sided technique is Power Shedding, which is supported autonomously by the ONU [17]. With Power Shedding, the ONU turns off some of its components to reduce power consumption, while keeping the optical link in full function.

An OLT-sided power management technique has been proposed in [25], in which working ONUs of a TWDM-PON are organized to send and receive traffic over a minimum number of wavelengths, allowing the OLT to turn off some of its transceivers so as to save power. In a more recent work [33], the authors propose introducing a tuning device into the OLT, which will allow the wavelengths and transceivers to be shared across multiple TWDM-PONs, thus, enabling the aforementioned scheme to be used over multiple TWDM-PONs.

4.1.1 Protocol-based power management techniques

Protocol-based power management techniques do require signalling between the OLT and ONU. Well known examples of such techniques are the Doze and Cyclic sleep modes.

4.1.1.1 The Cyclic Sleep and Doze Modes

The ITU-T G.987.3 [15] introduced two power saving modes for PON systems: the Cyclic Sleep and Doze modes. In both modes, the ONU alternates between an active phase and a power saving phase, as shown in Figure 4.1. The transition between the active phase and the power saving phase requires signalling information exchange between the OLT and the ONU. During a power saving phase, the ONU can alternate between two states: a full power state, referred as the Aware state, and a low power state.

The difference between the Cyclic Sleep and Doze modes lies in the semantics of the respective low power states (see Figure 4.2). In the low power state of the Cyclic Sleep mode, known as the *Asleep* state, the ONU maintains both transmitter and receiver

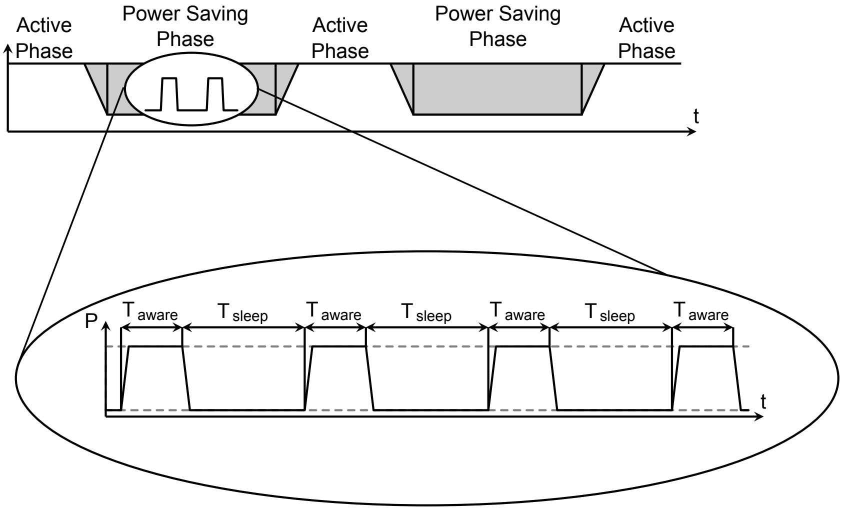
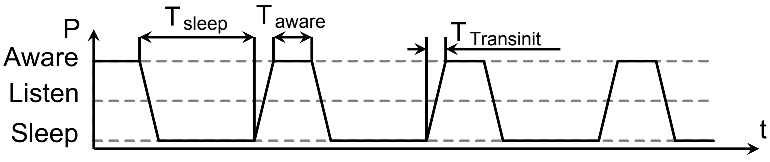
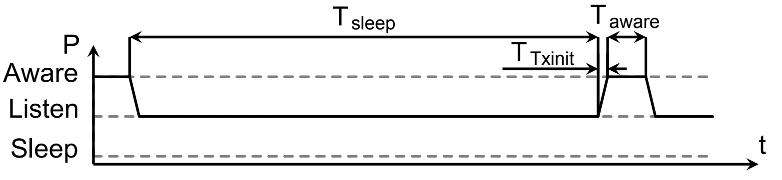


Figure 4.1: Active and power saving phases for the *Cyclic Sleep* and *Doze* Modes.

`OFF`, thus becoming unable to receive or send any traffic during the low power state. In the low power state of the Doze mode, known as the *Listen* state, the ONU keep the transmitter `OFF` and the receiver `ON`, thus the ONU can still "listen" the traffic. In both modes, the ONU can detect and respond to a local stimulus, that can arise, for example, when someone picks up the phone. Only for the Doze mode the ONU maintains the ability to respond to an external stimulus during the low power state.



(a) Cyclic Sleep Mode



(b) Doze Mode

Aware: Tx ON/Rx ON Listen: Tx OFF/Rx ON Sleep: Tx OFF/Rx OFF

Figure 4.2: ONU Power Consumption in the Cyclic Sleep and Doze Modes.

Figure 4.2 illustrates the power consumption during a power saving phase for the Cyclic Sleep and Doze modes. Table 4.1 describes the Cyclic Sleep and Doze mode parameters.

Table 4.1: Cyclic Sleep mode and Doze mode parameters

Parameter	Description
$\mathrm{T_{aware}}$	$\mathrm{T_{aware}}$ is the minimum sojourn in the Sleep/Doze Aware state.
$\mathrm{T_{sleep}}$	$\mathrm{T_{sleep}}$ is the maximum sojourn in both Asleep and Listen states.
$\mathrm{T_{Txinit}}$	$\mathrm{T_{Txinit}}$ is the transmitter initialization time, i.e. the transition overhead from the Listen state to the Aware state.
$\mathrm{T_{Transinit}}$	$\mathrm{T_{Transinit}}$ is the full transceiver initialization and synchronization time, i.e. the transition overhead from the Asleep state to the Aware state.
$\mathrm{T_{alerted}}$	$\mathrm{T_{alerted}}$ is the maximum sojourn in the Alerted Sleep/Doze state.
$\mathrm{T_{eri}}$	$\mathrm{T_{eri}}$ is the maximum time interval the OLT can stay without receiving any burst from the ONU before declaring a handshake violation.
$\mathrm{T_{hold}}$	$\mathrm{T_{hold}}$ is the minimum sojourn in the Active Held state.

The Cyclic Sleep and Doze modes work through state machines (see Figures 4.3 and 4.4). Each ONU has its own state machine, and the OLT keeps one state machine for each ONU. The OLT has some control over the ONU state machine through signalling exchange between the OLT and the ONU. The OLT sends Sleep Allow (SA) PLOAM messages to the ONU in order to allow (SA (ON)) or disallow (SA (OFF)) the transition to a power saving phase. The ONU sends Sleep Request (SR) PLOAM messages to the OLT in order to notify the start or the end of a power saving phase. There are three kinds of SR messages: SR(Awake), that notifies the end of a power saving phase; SR(Sleep), that notifies the beginning of a power saving phase for the Cyclic Sleep mode; and SR(Doze), that notifies the beginning of a power saving phase for the Doze mode. Besides these messages, there are also some events that control the transitions between the phases. The events at the ONU and the OLT are described in table 4.2.

Table 4.2: Cyclic Sleep mode and Doze mode events

Event	Description
Local Wake-up Indication (LWI)	The LWI event indicates that the ONU cannot enter or stay in a power saving phase.
Local Sleep Indication (LSI)	The LSI event indicates that the ONU should start a power saving phase of the Cyclic Sleep mode.

Event	Description
Local Doze Indication (LDI)	The LDI event indicates that the ONU should start a power saving phase of the Doze mode.
Forced Wake-up Indication (FWI)	The FWI is a flag of an allocation structure that the OLT sends to the ONU in order to end a power saving phase.
OLT-LWI	The OLT-LWI event indicates that the ONU should be in the active phase.
!OLT-LWI	The !OLT-LWI event indicates that the ONU should not be in the active phase.

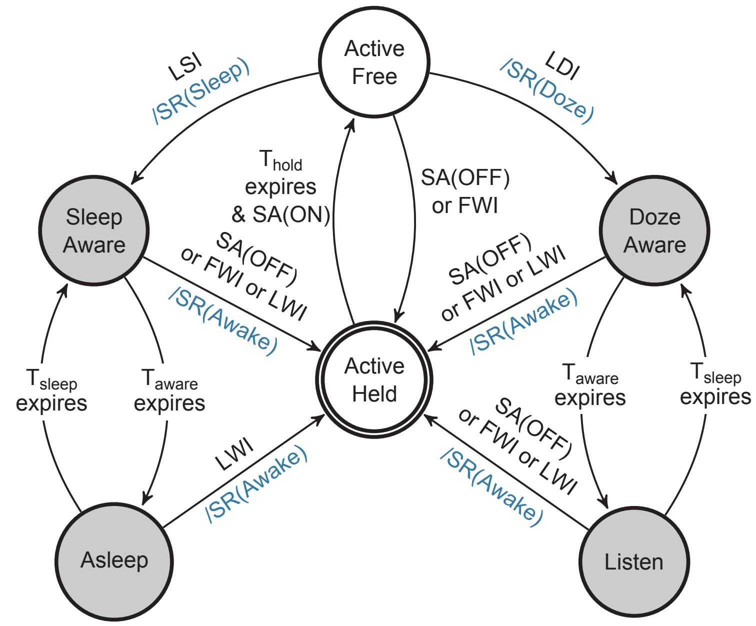


Figure 4.3: ONU State Machine for the Cyclic Sleep and Doze modes.

The states of the ONU state machine (see Figure 4.3) are described in table 4.3.

Table 4.3: Cyclic Sleep and Doze mode states for the ONU state machine

State	Tx	Rx	Description
Active Held	`ON`	`ON`	The Active Held state is part of the active phase. The ONU is not allowed to start a power saving phase. The minimum sojourn in this state is determined by T_{hold}.

State	Tx	Rx	Description
Active Free	`ON`	`ON`	Active Free state is part of the active phase. The ONU is allowed to locally decide if it should start a power saving phase. The transition to a power saving phase occurs with an LSI, for the Cyclic Sleep mode, or an LDI, for the Doze mode.
Sleep Aware Doze Aware	`ON`	`ON`	The Sleep/Doze Aware state is the full power state of a power saving phase. If no wake-up stimulus occurs before $\mathrm{T}_{\mathrm{aware}}$ expires, i.e. no LWI nor the arrival of an FWI or an SA (OFF) from the OLT, then the ONU transits to the low power state. Otherwise, if a wake-up stimulus do occur, then ONU will return immediately to the Active Held state.
Listen	`OFF`	`ON`	The Listen state is the low power state of the Doze mode. The ONU turns `OFF` only the transmitter, maintaining the receiver `ON`. The ONU “listens” to the downstream traffic, and can detect local stimulus, such as an LWI, and external stimulus, such as FWI or SA (OFF) messages. If no waking up stimulus occurs before $\mathrm{T}_{\mathrm{sleep}}$ expires, then the ONU will return to the Doze Aware state. Otherwise, if a wake up stimulus occurs, the ONU will return to the Active Held state.
Asleep	`OFF`	`OFF`	The Asleep state is the low power state of the Cyclic Sleep mode. The ONU turns `OFF` both receiver and transmitter, but maintain the ability to wake up through a local stimulus. If no LWI occurs before $\mathrm{T}_{\mathrm{sleep}}$ expires, then the ONU will return to the Sleep Aware state. Otherwise, if an LWI do occur, then the ONU will return immediately to the Active Held state.

The states of the OLT state machines (see Figure 4.4) are described in Table 4.4.

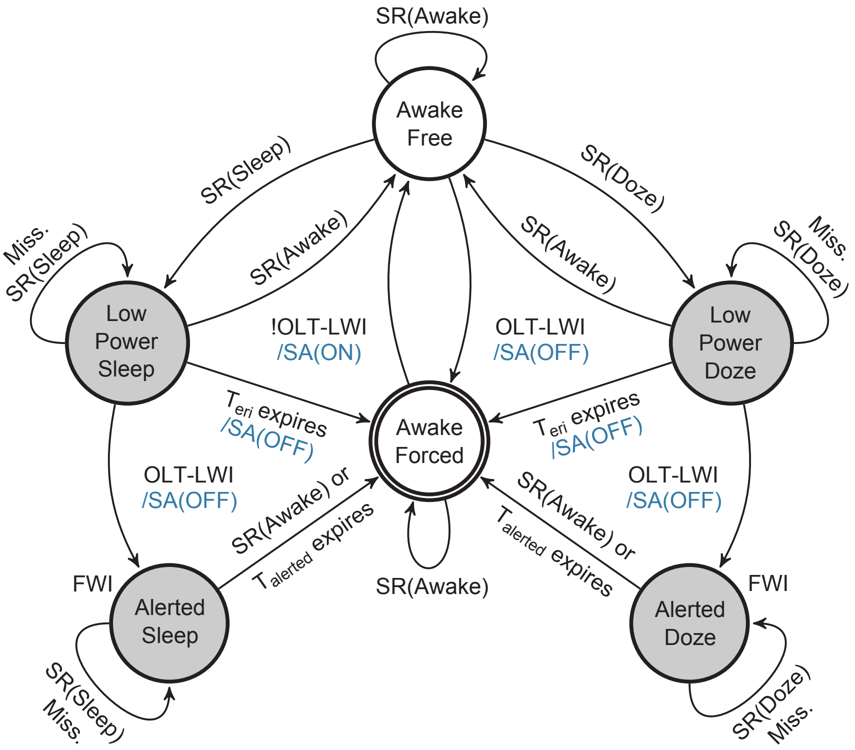


Figure 4.4: OLT State Machine for the Cyclic Sleep and Doze modes.

Table 4.4: Cyclic Sleep and Doze mode states for the OLT state machine

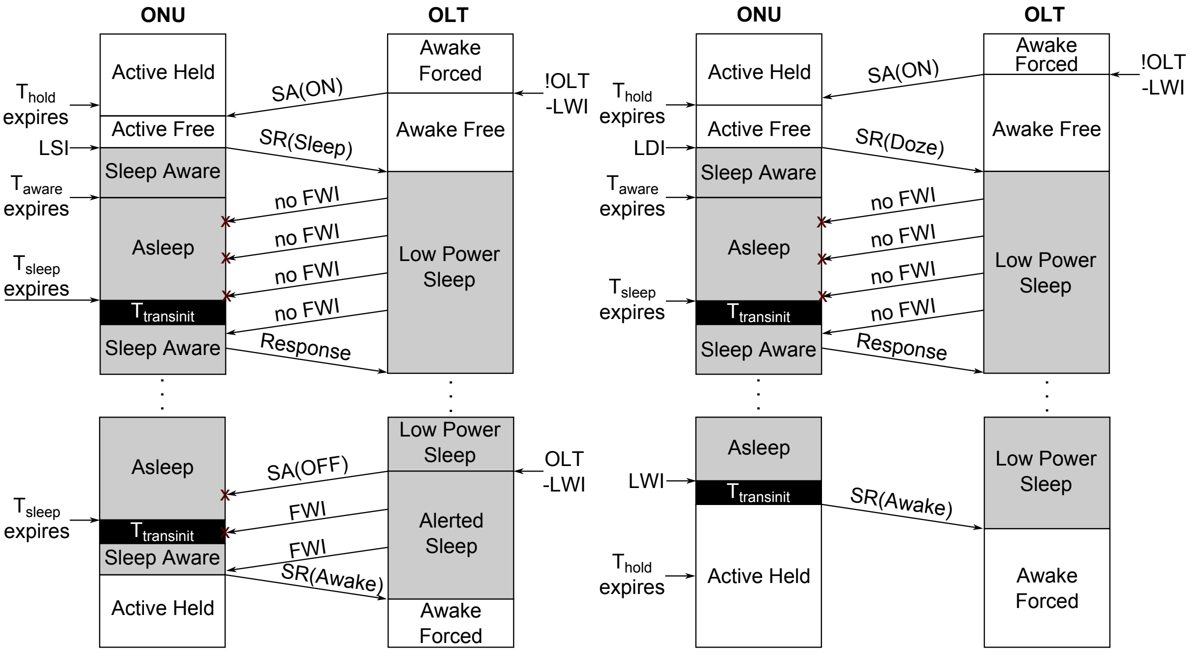
State	Description
Awake Forced	In the Awake Forced state, the OLT expects the ONU to be in the active phase, and forwards the downstream traffic normally. On transition into this state, the OLT send an SA (OFF) message to the ONU, thus revoking the permission for the ONU to enter a power saving phase. The OLT exits this state upon a !OLT-LWI event.
Awake Free	In the Awake Free state, the OLT expects the ONU to be in a full power state, and forwards the downstream traffic normally. On the transition into this state, the OLT send an SA (ON) message to the ONU, i.e., the OLT already gave permission for the ONU to enter a power saving phase, and is ready to accept a PLOAM message from the ONU indicating the transition to a power saving phase, such as SR (Sleep) and SR (Doze).

State	Description
Low Power Sleep Low Power Doze	In the Low Power Sleep/Doze state, the OLT expects the ONU to be in a power saving phase, thus expecting only intermittent responses from the ONU. In the Low Power Doze state, the OLT forwards the downstream traffic normally, whereas in the Low Power Sleep state, the OLT may buffer the downstream traffic, since the ONU may be with its receiver turned off. If the OLT does not receiver anything from the ONU for a time period bigger than T_{eri}, the OLT declares a handshake violation and returns to the Awake Forced state.
Alerted Sleep Alerted Doze	In the Alerted Sleep/Doze state, the OLT expects the ONU to be in a power saving phase, and is trying to wake-up the ONU. On the transition to this state, the OLT send a SA (OFF) to the ONU in order to wake-up the ONU. Also, the OLT sets the FWI bit in every allocation to the ONU. The OLT treats the downstream traffic the same way it treated during the Low Power Sleep/Doze state. The OLT goes back to the Awake Forced stated if it receives a SR (Awake) from the ONU or if T_{alerted} expires.

In order to better illustrate how the OLT and ONU state machines work, Figures 4.5 and 4.6 show examples of the signalling exchange during the Cyclic Sleep and Doze modes, in which the power saving phase, represented in the figures by the gray area, is terminated by either an OLT-LWI event at the OLT, or by an LWI event at the ONU.

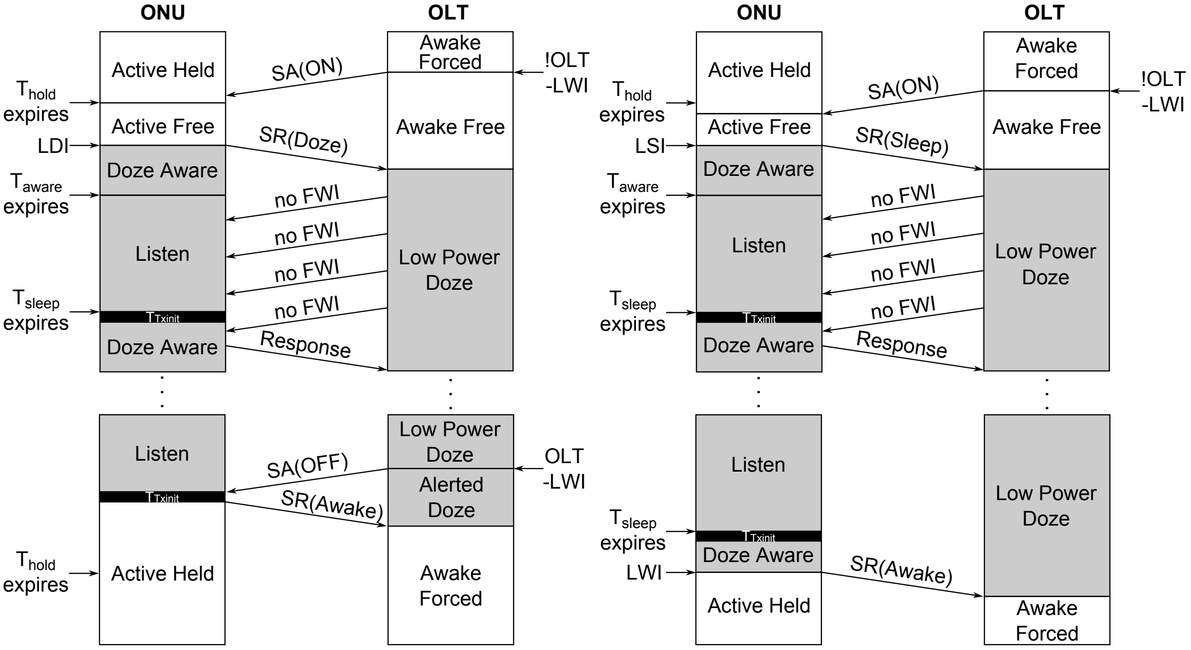
Notice that in Figure 4.5(a), even after the OLT had already decided to wake-up the ONU, the OLT still had wait, in the Alerted Sleep state, for T_{sleep} to expire and the ONU to return to the Aware state; whereas for the Doze mode, the ONU woke up almost immediately (see Figure 4.6(a)). Moreover, while in the Alerted Sleep state, the OLT may buffer (or discard) the downstream traffic, which means that a long sojourn in the Alerted Sleep state will degrade the quality of service. However, during the Alerted Doze, the OLT forwards the downstream traffic normally, thus, not only the sojourn in the Alerted Doze is much smaller, but it also has almost no impact in the service.

When the power saving phase is terminated by the ONU local event LWI, as shown in



(a) (b)

Figure 4.5: Examples of signalling exchange for the Cyclic Sleep mode being terminated by (a) OLT-LWI event and (b) LWI event.



(a) (b)

Figure 4.6: Example of signalling exchange for the Doze mode being terminated by (a) OLT-LWI event and (b) LWI event.

Figures 4.5(b) and 4.6(b), the wake-up process is much simpler than for an external stimulus. For both the Cyclic Sleep and Doze modes, the ONU simply transits from the low power state to the Active Held state, and, upon transition into the Active Held state, the ONU sends an SR(Awake) to inform the OLT that the ONU terminated the power saving phase. Observe that the time required for the ONU to terminate the power saving phase upon a local event is not affected by $\mathrm{T_{sleep}}$, even for the Cyclic Sleep mode. The sole timing parameter that has effect on the ONU-initiated wake-up is the transition overhead from the low power state to a full power state, i.e. $\mathrm{T_{Transinit}}$ parameter for the Cyclic Sleep mode, and $\mathrm{T_{Txinit}}$ for the Doze mode.

It is worth noticing that, in Figures 4.5 and 4.6, the ONU can only start a power saving phase after both the !OLT-LWI and LSI/LDI events occurred, whereas the ONU initiates the wake-up process as long as either an LWI at the ONU, or an OLT-LWI at the OLT occurs. Summarizing, while the timing parameters $\mathrm{T_{sleep}}$ and $\mathrm{T_{aware}}$ determine the sojourn in the low power and Aware states, respectively, the timing parameters $\mathrm{T_{Transinit}}$ and $\mathrm{T_{Txinit}}$ determine the transition overhead from the low power state to the Aware state. The implementation of the LWI, OLT-LWI, LSI, LDI and !OLT-LWI activation criteria determines if an ONU will start a power saving phase, and, once in a power saving phase, these parameters determine when the ONU will end the power saving phase. None of these parameters are specified on the recommendations.

When the OLT is in the Low Power state, it keeps sending normal allocations to the ONU (which is represented in Figures 4.5 and 4.6 by the "no FWI" messages since the FWI bit is not set in these allocations) even though it is aware that the ONU may not respond to these allocations. However, it is fundamental for the ONU to respond these allocations once in a while. Thus, the ONU must sojourn in the Aware state long enough to respond to these allocations. In other words, the $\mathrm{T_{aware}}$ value is chosen based on how long it takes for an ONU to receive and respond an allocation, i.e. $\mathrm{T_{aware}}$ must be bigger than the maximum duration of a handshake.

Before deciding on a value for $\mathrm{T_{sleep}}$, the OLT must consider that, upon entering the Asleep state, the ONU does not receive any message until $\mathrm{T_{sleep}}$ expires, thus it cannot respond to an external stimulus immediately. So, choosing a proper value for $\mathrm{T_{sleep}}$ in the Cyclic Sleep mode is very important. The $\mathrm{T_{sleep}}$ value for the Cyclic Sleep mode is chosen based on how long the OLT can afford to wait for the ONU come back to full power operation. As for the Doze mode, since the ONU can still respond to an external stimulus, the only concern the OLT has for $\mathrm{T_{sleep}}$ is that it must ensure that the ONU returns to the Aware state once in a while to assure that the ONU has not been dead or stolen. Therefore, $\mathrm{T_{sleep}}$ can be several times bigger for the Doze mode than for the Cyclic Sleep mode.

The parameters $\mathrm{T_{Transinit}}$ and $\mathrm{T_{Txinit}}$ are intrinsic to the ONU architecture, since $\mathrm{T_{Transinit}}$ is the transceiver initialization time, and $\mathrm{T_{Txinit}}$ is the transmitter initialization time. Choosing an ONU architecture with a fast transition between low power states and full power states allows the ONU to spend more time in low power states, thus improving the overall energy efficiency. As an example of how important $\mathrm{T_{Transinit}}$ and $\mathrm{T_{Txinit}}$ are, in [20] the authors compare three different ONU architectures, in which, an ONU with a low power consumption in the Asleep state had a big $\mathrm{T_{Transinit}}$, whereas an ONU with a small $\mathrm{T_{Transinit}}$ had a bigger power consumption in the Asleep state. The ONU with a big $\mathrm{T_{Transinit}}$ failed in achieving an effective energy saving under realistic traffic, indicating that an ONU with a bigger power consumption and a small $\mathrm{T_{Transinit}}$ may be a more energy efficient solution than the former.

Besides the timing parameters, the local and external stimuli are also very important to the performance of the Cyclic Sleep and Doze modes, as they define when the ONU initiates and terminates a power saving phase. A simple implementation of the LSI/LDI and !OLT-LWI events could be a timer that expires after some time without receiving any traffic.

Even though the Cyclic Sleep and Doze modes can improve the energy efficiency in PON systems, they lead to some limitations. First, the OLT and the ONU need to decide on which mode to enter: either Cyclic Sleep mode or Doze mode. Second, in the Cyclic Sleep mode, in order to probe for external wake-up stimulus, the ONU must periodically turn `ON` both receiver and transmitter, even though turning only the receiver `ON` is sufficient. Third, in Doze mode the ONU maintains the receiver always `ON`, even when there is no traffic for that ONU. Fourth, there are too many redundant states in the Cyclic Sleep and Doze modes state machines, making it needlessly complex. Last but not least, there is no technical reason to maintain the separation of the two modes.

Chapter 5 The Watchful Sleep Mode

This chapter presents the Watchful Sleep mode, which is a new power management mode that unifies the Cyclic Sleep and Doze modes into a single power saving mode. The Watchful Sleep mode was proposed in one of the papers published during the development of this dissertation [23] and became a novel ITU-T standard for ONU power saving in 2014.

5.1 The Watchful Sleep Mode

In the Watchful Sleep mode, just as in the Cyclic Sleep and Doze modes, the ONU can alternate between active and power saving phases. If the Watchful Sleep mode is supported, there is no need to negotiate on which power saving mode to employ, therefore there is no potential disagreement.

The difference between the Watchful Sleep mode and the other two modes (the Cyclic Sleep mode and the Doze mode) is in the power saving phase. In the power saving phase, the Watchful Sleep mode alternates between three different power levels: a full power level, an intermediate power level and a low power level (see Figure 5.1). In the full power level, the ONU maintains both receiver and transmitter `ON`, just like in the Sleep/Doze Aware states. In the intermediate power level, the ONU turns the transmitter `OFF`, and keeps the receiver `ON`, just like in the low power state of the Doze mode, the Listen state. In the low power level, the ONU turns `OFF` both the receiver and transmitter, just like in the low power state of the Cyclic Sleep mode, the Asleep state [23]. In sum, the Watchful Sleep mode has a *single* low power state, the *Watch* state, with two power levels: the intermediate level, referred to as Rx `ON`; and the low power level, referred to as Rx `OFF`.

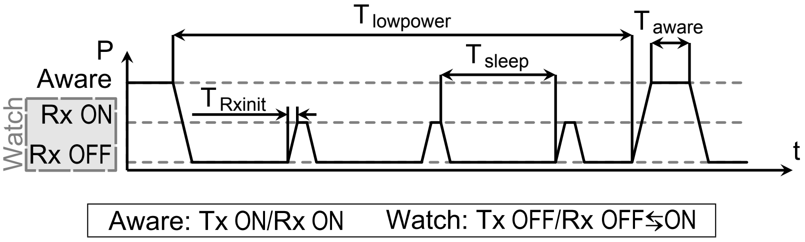


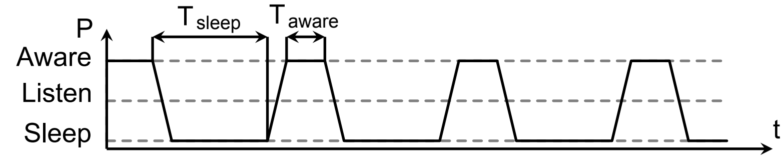
Figure 5.1: ONU Power Consumption in the Watchful Sleep Mode.

Observe in Figure 5.1 that, besides having T_{sleep} and T_{aware}, there are two new timing parameters: T_{lowpower} and T_{Rxinit}. Table 5.1 describes the parameters of the Watchful Sleep mode.

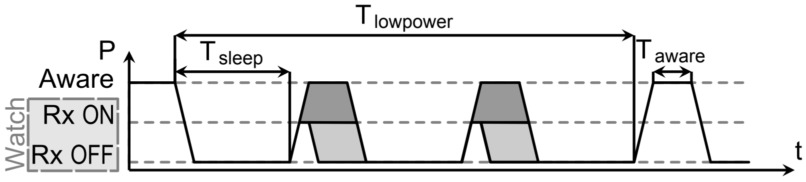
Table 5.1: Watchful Sleep mode parameters

Parameter	Description
T_{aware}	T_{aware} is the minimum sojourn in the WSleep Aware state.
T_{sleep}	T_{sleep} is the maximum sojourn in the Rx `OFF` power level.
T_{lowpower}	T_{sleep} is the maximum sojourn in the Watch state.
T_{Txinit}	T_{Txinit} is the transmitter initialization time, i.e. the transition overhead from the Rx `ON` power level to the Aware state.
T_{Rxinit}	T_{Rxinit} is the receiver initialization and synchronization time, i.e. the transition overhead from the Rx `OFF` power level to the Rx `ON` power level.
$T_{\text{Transinit}}$	$T_{\text{Transinit}}$ is the full transceiver initialization and synchronization time, i.e. the transition overhead from the Rx `OFF` power level to the Aware state.
T_{alerted}	T_{alerted} is the maximum sojourn in the Alerted Watch state.
T_{eri}	T_{eri} is the maximum time interval the OLT can stay without receiving any burst from the ONU before declaring a handshake violation.
T_{hold}	T_{hold} is the minimum sojourn in the Active Held state.

While T_{sleep} in the Cyclic Sleep and Doze modes determines the maximum sojourn in the low power states, in the Watchful Sleep mode T_{sleep} determines the maximum sojourn in the Rx `OFF` power level. The ONU sojourns in the Rx `ON` power level until the ONU receives an allocation with the FWI bit not set only (see Figure 5.6). If the OLT sends an allocation in each frame, then the sojourn in the Rx `ON` power level can be as small as one frame (125 μs).

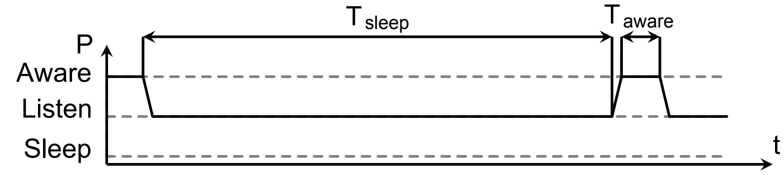


(a) Cyclic Sleep Mode

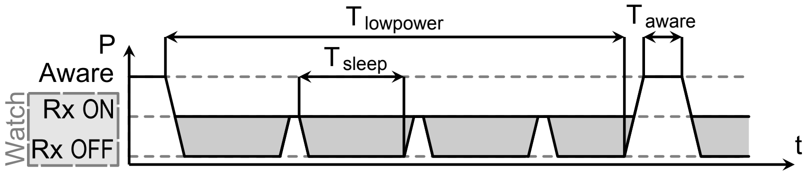


(b) Watchful Sleep Mode

Figure 5.2: Comparison of the ONU power consumption between the Cyclic Sleep mode and the Watchful Sleep mode under identical operating parameters.



(a) Doze Mode



(b) Watchful Sleep Mode

Figure 5.3: Comparison of the ONU power consumption between the Doze mode and the Watchful Sleep mode under identical operating parameters.

The advantage of having two distinct power levels in the Watch state lies on the fact that the ONU can maintain only the necessary components `ON`. That is, instead of checking for external stimulus by turning both transmitter and receiver `ON`, like in the Cyclic Sleep mode, the ONU can and will check the traffic with only the receiver `ON`. After assuring that there are no external wake-up stimuli, the ONU will not needlessly maintain the receiver `ON`, like in the Doze mode. Figures 5.2 and 5.3 show a comparison of the ONU power consumption between the Watchful Sleep mode and the other two modes. The gray areas indicate the power efficiency gain.

In the Watchful Sleep mode, the PLOAM messages SR(Sleep) and SR(Doze) are merged innto the SR(WSleep) message, whereas the PLOAM messages SR(Awake), SA(ON) and SA(OFF) remain the same. The events LWI, OLT-LWI, !OLT-LWI and

FWI are the same for the Watchful Sleep mode, however, the LSI and LDI are unified in just one event, the Local Low Power Indication (LPI) . Table 5.2 describes the events at and ONU and OLT for the Watchful Sleep mode.

Table 5.2: Watchful Sleep mode events

Event	Description
LWI	The LWI event indicates that the ONU cannot enter or stay in a power saving phase.
LPI	The LPI event indicates that the ONU should start a power saving phase.
FWI	The FWI is a flag of an allocation structure that the OLT sends to the ONU in order to end a power saving phase.
OLT-LWI	The OLT-LWI event indicates that the ONU should be in the active phase.
!OLT-LWI	The !OLT-LWI event indicates that the ONU should not be in the active phase.

5.1.1 The State Machines for the Watchful Sleep Mode

The OLT and ONU state machines In the Watchful Sleep mode are a simplified version of the respective state machines for the Cyclic Sleep and Doze modes.

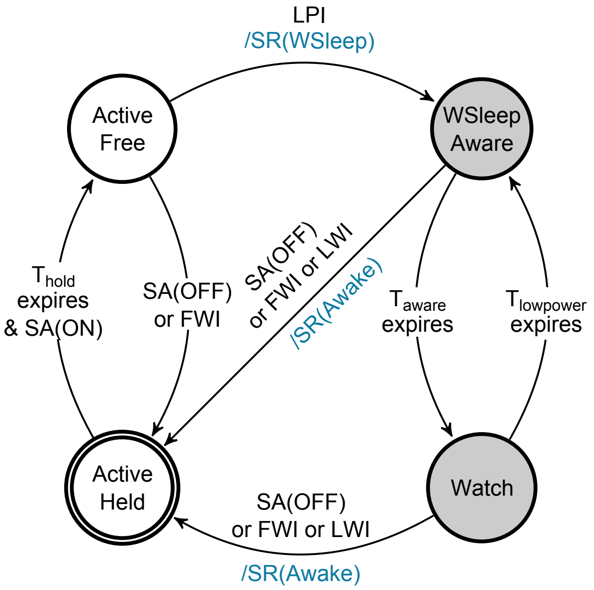


Figure 5.4: ONU State Machine for the Watchful Sleep Mode.

In the ONU state machine (Figure 5.4), the Active Held and Active Free states are the same as in the Cyclic Sleep and Doze modes state machines. The full power states Sleep Aware and Doze Aware were merged into the *single* WSleep Aware state. The low power states, Asleep and Listen, were merged into the Watch state. Table 5.3 has a description on the ONU states for the Watchful Sleep mode.

Table 5.3: Watchful Sleep mode states for the ONU state machine

State	Tx	Rx	Description
Active Held	`ON`	`ON`	The Active Held state is part of the active phase. The ONU is not allowed to start a power saving phase.
Active Free	`ON`	`ON`	Active Free state is part of the active phase. The ONU is allowed to locally decide if it should start a power saving phase. The transition to a power saving phase occurs with an LPI.
WSleep Aware	`ON`	`ON`	The WSleep Aware state is the full power level state of a power saving phase. If no wake-up stimulus occurs before T_{aware} expires, i.e. no LWI nor the arrival of an FWI or an SA (OFF) from the OLT, then the ONU transits to the low power state. Otherwise, if a wake-up stimulus do occur, then ONU will return immediately to the Active Held state.
Watch	`OFF`	`OFF`⇄`ON`	During the Watch state, the ONU maintains the transmitter `OFF`, but periodically turns the receiver `ON` for a short time to check for external wake-up stimuli. If no waking up stimulus occurs before T_{lowpower} expires, then the ONU will return to the WSleep Aware state. Otherwise, the ONU will return to the Active Held state.

In the OLT state machine (Figure 5.5), the states Awake Forced and Awake Free are the same as in the Cyclic Sleep and Doze modes state machines. The states Low Power Sleep and Low Power Doze were merged into the *single* Low Power Watch state, and

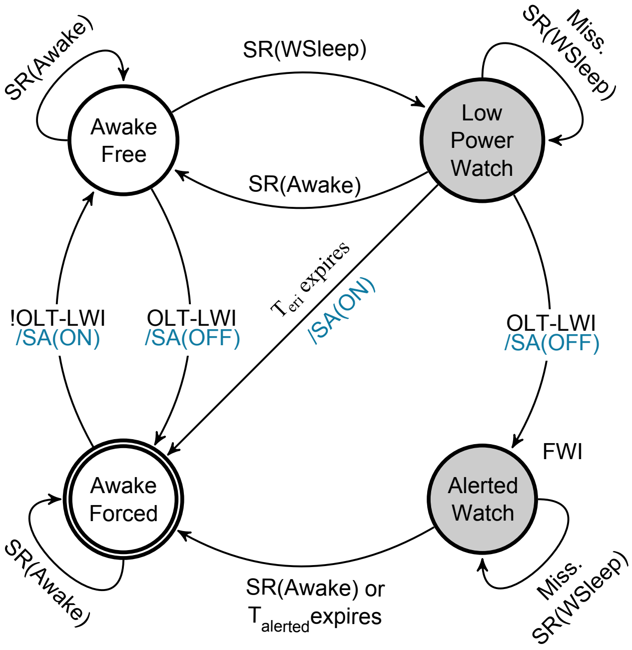


Figure 5.5: OLT State Machine for the Watchful Sleep Mode.

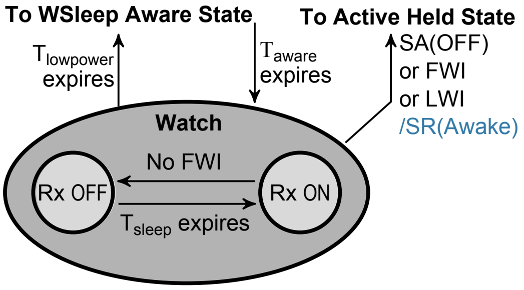


Figure 5.6: Internal Semantics of the New Watch State.

the state Alerted Sleep and Alerted Doze were merged into *single* the Alerted Watch state. The states of the OLT state machine for the Watchful Sleep mode are described in Table 5.4.

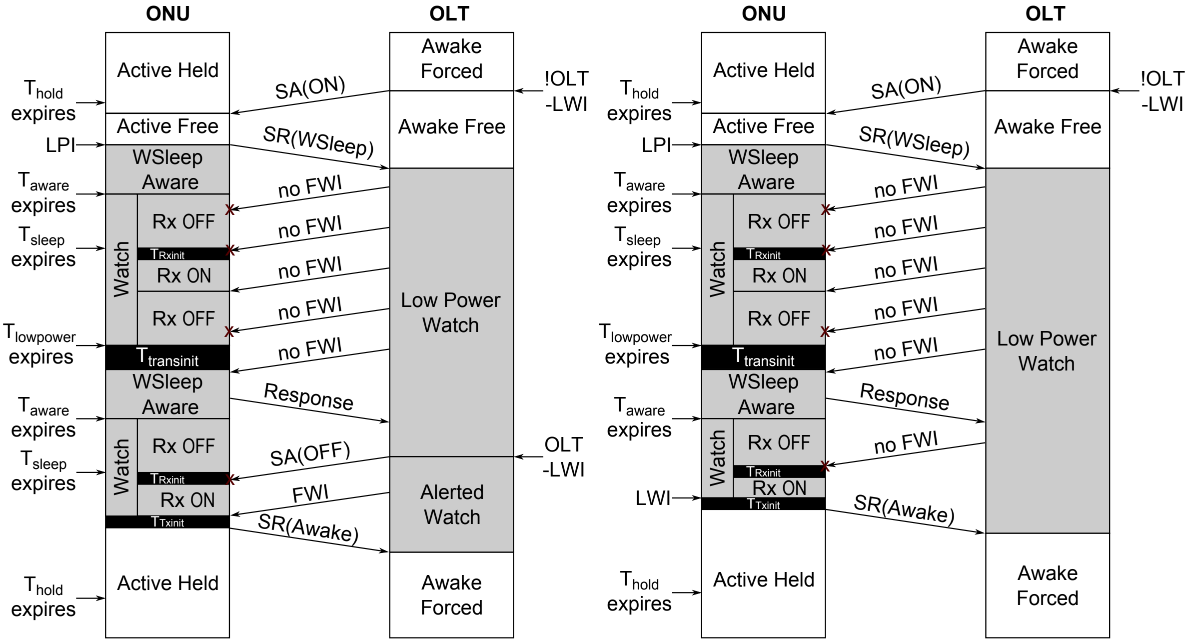
Table 5.4: Watchful Sleep mode states for the OLT state machine

State	Description
Awake Forced	In the Awake Forced state, the OLT expects the ONU to be in the active phase, and forwards the downstream traffic normally. On transition into this state, the OLT send an SA (OFF) message to the ONU, thus revoking the permission for the ONU to enter a power saving phase. The OLT exits this state upon a !OLT-LWI event.

State	Description
Awake Free	In the Awake Free state, the OLT expects the ONU to be in a full power state, and forwards the downstream traffic normally. On the transition into this state, the OLT send an SA (ON) message to the ONU, i.e., the OLT already gave permission for the ONU to enter a power saving phase, and is ready to accept a PLOAM message from the ONU indicating the transition to a power saving phase, such as SR (WSleep).
Low Power Watch	In the Low Power Watch state, the OLT expects the ONU to be in a power saving phase, thus expecting only intermittent responses from the ONU. In the Low Power Watch state, the OLT may buffer the downstream traffic, since the ONU may be with its receiver turned `OFF`. If the OLT does not receiver anything from the ONU for a time period bigger than $\mathrm{T_{eri}}$, the OLT declares a handshake violation and returns to the Awake Forced state.
Alerted Watch	In the Alerted Watch state, the OLT expects the ONU to be in a power saving phase, and is trying to wake-up the ONU. On the transition to this state, the OLT send a SA (OFF) to the ONU in order to wake-up the ONU. Also, the OLT sets the FWI bit in every allocation to the ONU. The OLT treats the downstream traffic the same way it treated during the Low Power Watch state. The OLT goes back to the Awake Forced stated if it receives a SR (Awake) from the ONU or if $\mathrm{T_{alerted}}$ expires.

5.1.2 Signalling Exchange during the Watchful Sleep Mode

In order to better illustrate the difference between the Watchful Sleep mode and the other two modes, the Cyclic Sleep and Doze modes, Figure 5.7 shows two examples of the signalling exchange during the Watchful Sleep mode. The major difference lies, as expected, on the Watch state semantics, as shown in Figure 5.6. The energy consumption during the Watch state is the combination of the energy consumption during the Rx `OFF` power level, Rx `ON` power level and during the transition from Rx `OFF` to Rx `ON`. Then, in order to maximize the energy efficiency for the Watch state, one must: 1) maximize the sojourn in Rx `OFF`, by maximizing $\mathrm{T_{sleep}}$; 2) minimize the



(a) (b)

Figure 5.7: Example of signaling exchange for the Watchful Sleep mode being terminated by (a) OLT-LWI event and (b) LWI event.

sojourn in the Rx `OFF`, by sending an allocation to the ONU as frequent as possible; and, if possible, 3) minimize the transition overhead from Rx `OFF` to Rx `ON` (T_{Rxinit}).

Notice that, when in the Low Power Watch state, the OLT keeps sending normal allocations with the FWI bit not set. The ONU, if in the Watch state, will only receive some of these allocations (when in the **Rx** `ON` power level), and will only respond these allocations after $T_{lowpower}$ expires or if the power saving phase is terminated by a wake-up stimulus. Therefore, the main concern when defining a value for the $T_{lowpower}$ parameter is with the required frequency of bi-directional handshakes, just like when determining a value for T_{sleep} in the Doze mode.

In the first signalling exchange example (Figure 5.7(a)), the power saving phase is terminated by the occurrence of an OLT-LWI event at the OLT. Observe that, after the the OLT-LWI event, if the ONU is in the the Rx `OFF` power level, the ONU will only receive the external wake-up stimulus after T_{sleep} or $T_{lowpower}$ expire, or if the power saving phase is interrupted by an local wake-up indication. Thus, T_{sleep} must be configured based on how long the OLT can afford to wait for the ONU to return to a full power state, just like when configuring T_{sleep} for the Cyclic Sleep mode.

In the second signalling exchange example (Figure 5.7(b)), the power saving phase is terminated by an LWI event. The wake-up process is much simpler with the LWI, because, regardless of the state, the ONU always maintains the ability to wake up with a local stimulus.

In the worst case, if the use of the Watchful Sleep mode is not feasible or not desirable, the OLT can configure the operating parameters to emulate either the Cyclic Sleep mode or the Doze mode. For emulation of the Cyclic Sleep mode, the OLT must configure the operating parameters in a way that the ONU will stay in Rx `OFF`, and never transit to Rx `ON` power level. By setting T_{lowpower} parameter to be equal or smaller than T_{sleep}, the Watch state will end before the transition to Rx `ON`, thus emulating the Cyclic Sleep mode. For emulation of the Doze mode, the parameters must be configured so the time interval in the Rx `OFF` is 0, which can be achieved by configuring $T_{\text{sleep}} = 0$.

Chapter 6 Performance Evaluation

In order to evaluate the performance of protocol-based power management mechanisms in PONs, a PON simulator was developed using the component-based C++ simulation library and framework OMNeT++ [34]. This simulator is an updated version of the one used in [23, 35, 36]. This chapter explains the structure of the developed PON simulator, and also presents and analyzes the results on the energy saving and the mean delays as a function of the network load and T_{sleep} for the three power management modes (Cyclic Sleep mode, Doze mode and Watchful Sleep mode) under different scenarios for XG-PON and TWDM-PON systems.

6.1 The PON Simulator

OMNeT++ is an object-oriented modular discrete event based framework for network simulations that provides infrastructure and tools for writing simulations models [34]. The PON simulator developed in OMNeT++ consists of a set of modules that communicate with message passing. Figure 6.1 shows the modules that composes the developed simulation model on a simulation scenario.

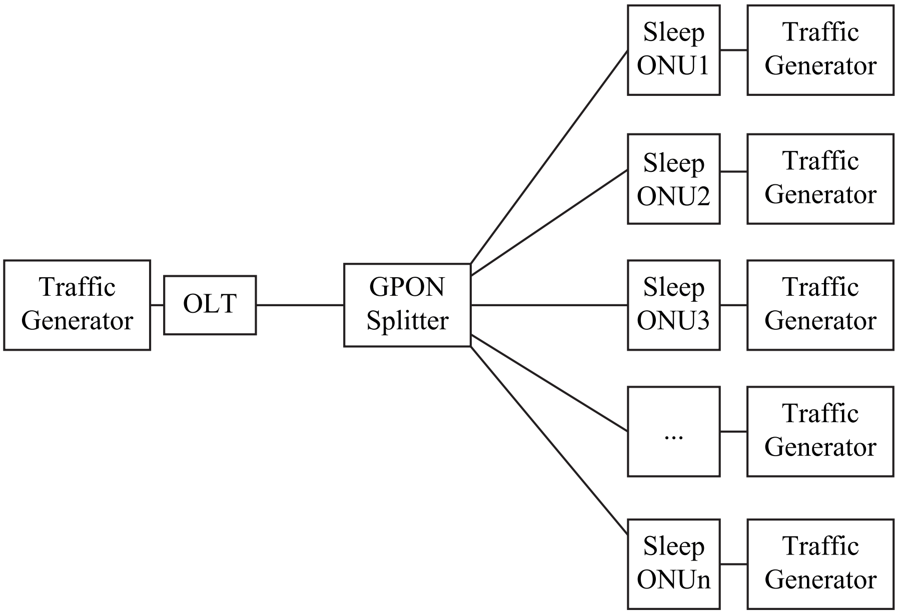


Figure 6.1: Basic structure of the simulated networks.

The `Traffic Generator` module is an adaptation of the traffic generator presented in [37] that generates self-similar traffic with a Pareto distribution using the method described in [38]. The packet size was configured to be uniformly distributed between 64 and 1518 bytes in every simulation. Besides generating the traffic, these modules were adapted to also measure the end-to-end delay. The `GPON Splitter` emulates an optical splitter and was inspired on the Optical Splitter module found in [39], which is a basic implementation of E-PON for OMNeT++. The `OLT` and `Sleep ONU` modules are explained in Sections 6.1.1 and 6.1.2.

6.1.1 The `ONU` Module

The `Sleep ONU` module is the compound module that represents an ONU with the Watchful Sleep mode implemented. This module is formed by 3 sub-modules: the `TRx ONU` module; the *Sleep Queue* Module; and the `ONU` module (see Figure 6.2).

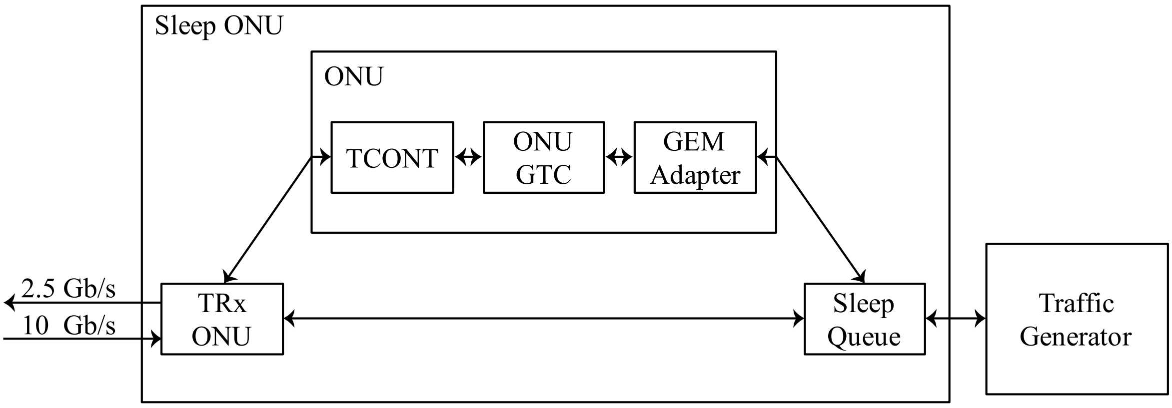


Figure 6.2: Architecture of the `Sleep ONU` module.

The `TRx ONU` module represents the ONU transceiver and is responsible for managing the Watchful Sleep state machines. When the `TRx ONU` is in the Rx `ON` power level, the ONU does not transmit any packet; and when in the Rx `OFF` power level, besides not transmitting any packet, the ONU also discards every received packet. The `Sleep Queue` module is a queue where the ONU buffers the upstream packets when in the Watch state. The direct connection between the `TRx ONU` and the `Sleep Queue` modules allows the `TRx ONU` to warn the `Sleep Queue` module when the ONU enters and exits the Watch state. The `Sleep Queue` module also uses this connection to inform the `TRx ONU` module of every packet arrival.

The `ONU` module is a compound module that represents an ONU without any power management capability. This module is also formed by 3 sub-modules: the `TCONT` module; the `ONU GTC` module; and the `GEM adapter` module. The `TCONT` module is responsible for maintaining every upstream burst contained in a time interval determined by the OLT, and for reporting the buffer occupancy to the OLT. The `ONU GTC` module is responsible for encapsulating the GEM frames from the `GEM Adapter` into an upstream GTC frame. The `GEM Adapter` is responsible for encapsulation SDUs into GEM frames and decapsulating GEM frames to SDUs.

6.1.2 The `OLT` Module

The `OLT` module is the compound module that represents an OLT. This module is formed by 3 sub-modules: the `Allocator` module; the `GEM Adapter` Module; and the `OLT GTC` module (see Figure 6.3).

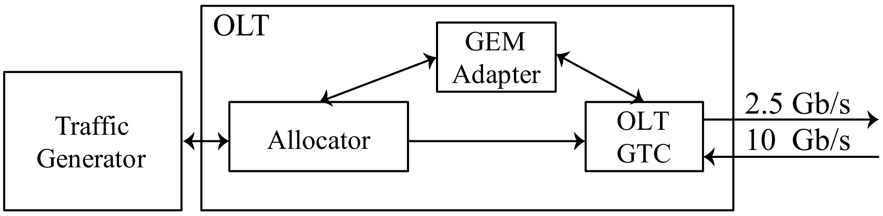


Figure 6.3: Architecture of the `OLT` module.

The `Allocator` module is responsible for providing random destinations to the downstream packets. The `GEM Adapter` module is the same as the `GEM Adapter` module at the ONU. The `OLT GTC` module is responsible for managing the Watchful Sleep state machines, encapsulating the GEM frames from the `GEM Adapter` into downstream GTC frame, and for allocating the time slots for the upstream bursts.

6.2 Simulation Results

The simulation results presented in this chapter are on the energy saving and the delays in both upstream and downstream directions under 5 different scenarios. Scenarios 1 to 3 considered a XG-PON system, whereas scenarios 4 and 5 considered a TWDM-PON system.

The primary performance measure, the energy saving (η), is the fraction of energy consumed with a given ONU power management mode compared to energy consumed in a full-power operation over an observation period, $\mathrm{T}_{\mathrm{observe}}$:

$$\eta = 1 - \frac{\mathrm{E_{ONU}}}{\mathrm{T_{observe}} \times \mathrm{P_{Aware}}}, \tag{6.1}$$

where $\mathrm{E_{ONU}}$ is the energy consumed by the ONU in a given power management mode during $\mathrm{T_{observe}}$. $\mathrm{P_{Aware}}$ is the power consumption for the Aware state.

6.3 Simulation Results for XG-PON systems

The simulation results for XG-PON systems considered an XG-PON1 system with 16 ONUs. We assumed a distance of 40 km between the ONUs and the OLT, corresponding to a propagation delay of 100 μs. The duration of the TDM cycle is set to 2ms. Static bandwidth allocation is used. Every simulation was repeated 5 times.

Tables 6.1 and 6.2 show the parameter sets used for Scenarios 1, 2 and 3. For the sake of generality, percentages for the power consumption of the XG-PON and TWDM-PON transceivers were considered in lieu of absolute values. The power consumption for the Aware state, referred to as $\mathrm{P_{aware}}$, is assumed as 100%; the power consumption for the Listen state, referred to as $\mathrm{P_{listen}}$, is assumed to be 40%; and the power consumption for the Asleep state, referred to a $\mathrm{P_{asleep}}$, is assumed to be 5%.

Table 6.1: Parameter set for Scenario 1

Parameter	Watchful Sleep Mode	Doze Mode	Cyclic Sleep Mode
$\mathrm{T_{lowpower}}$	100 s	–	–
$\mathrm{T_{sleep}}$	100 ms	100 s	100 ms
$\mathrm{T_{aware}}$	50 ms	50 ms	50 ms
$\mathrm{P_{aware}}$	100%	100%	100%
$\mathrm{P_{listen}}$	40%	40%	–
$\mathrm{P_{asleep}}$	5%	–	5%
$\mathrm{T_{Txinit}}$	1.5 ms	1.5 ms	–
$\mathrm{T_{Rxinit}}$	0.5 ms	–	–
$\mathrm{T_{Transinit}}$	1.5 ms	–	1.5 ms

The parameters $\mathrm{T_{aware}}$, $\mathrm{T_{sleep}}$, $\mathrm{T_{lowpower}}$, $\mathrm{T_{Txinit}}$, $\mathrm{T_{Rxinit}}$ and $\mathrm{T_{Transinit}}$ for Scenario 1 are defined in Table 6.1, and for Scenarios 2 and 3 are defined in Table 6.2. The values for $\mathrm{T_{Txinit}}$, $\mathrm{T_{Rxinit}}$ and $\mathrm{T_{Transinit}}$ were obtained in [18]. The parameter $\mathrm{T_{hold}}$ is set to 2ms, in order to hold the ONU in the Active Held state for at least one TDM cycle; $\mathrm{T_{alerted}}$ is set to $\mathrm{T_{sleep}} + \mathrm{T_{aware}} + \mathrm{T_{Transinit}}$ for the Cyclic Sleep mode, to $\mathrm{T_{sleep}} + \mathrm{T_{aware}} + \mathrm{T_{Txinit}}$

Table 6.2: Parameter set for Scenarios 2 and 3

Parameter	Watchful Sleep Mode	Doze Mode	Cyclic Sleep Mode
T_{lowpower}	10 s	–	–
T_{sleep}	10 ms	10 s	10 ms
T_{aware}	5 ms	5 ms	5 ms
P_{aware}	100%	100%	100%
P_{listen}	40%	40%	–
P_{asleep}	5%	–	5%
T_{Txinit} (ms)	3 ms	3 ms	–
T_{Rxinit} (ms)	2 ms	–	–
$T_{\text{Transinit}}$ (ms)	3 ms	–	3 ms

for the Doze mode, and to $T_{\text{lowpower}} + T_{\text{aware}} + T_{\text{Rxinit}} + T_{\text{Txinit}}$ for the Watchful Sleep mode to guarantee that the OLT will wait in the Alerted state long enough for the ONU to return to full power operation; and T_{eri} is set to T_{alerted} + 2ms, so that the OLT will not declare a handshake violation while the ONU is in a low power state.

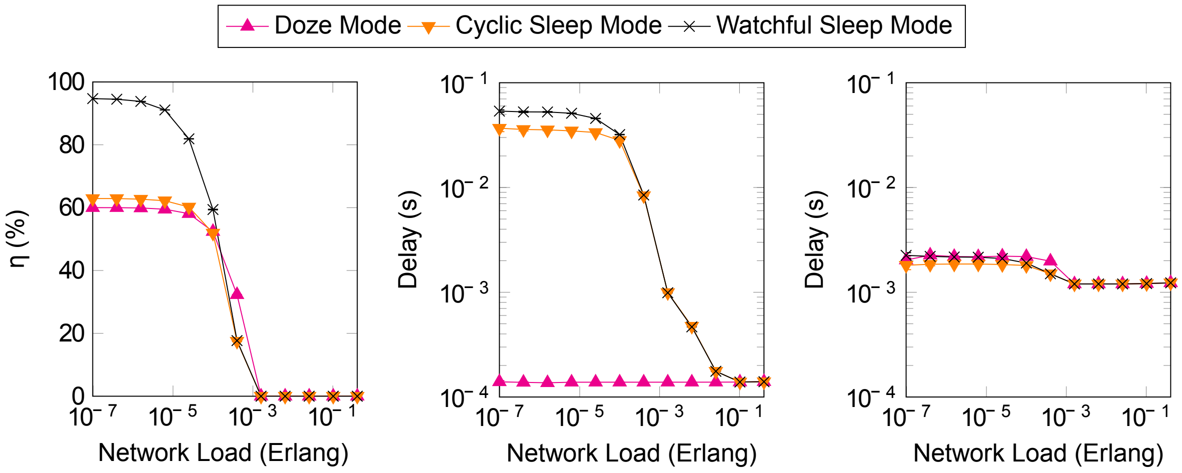
In Scenarios 1 and 2, the !OLT-LWI, is activated after 100 μs without any packet arrival, whereas LSI, LDI and LPI are activated after 1.3 ms without any packet arrival. The OLT-LWI and LWI are activated with the arrival of a packet. In Scenario 3, differently from Scenarios 1 and 2, the ONU activates !OLT-LWI, LSI, LDI and LPI as soon as the correspondent queue empties. The OLT-LWI is activated only 40 ms after a packet arrival and LWI is activated 50 ms after a packet arrival. Table 6.3 summarizes the indications activation criteria for Scenarios 1, 2 and 3.

Figures 6.4 and 6.5 show the energy saving, mean downstream delay and mean upstream delay for the three power management modes under Scenarios 1 and 2, respectively. All the results are presented as a functions of the network load, measured here in Erlang, which is the ratio between the arrival rate of packets and the PON service rate, i.e. 10 Gbps downstream and 2.5 Gbps upstream for XG-PON systems and 40 Gbps downstream and 10 Gbps upstream for TWDM-PON systems. Under both scenarios, the OLT in the Awake Forced state must wait for 100 μs without any packet arrival in order to enter the Awake Free state, and upon the transition from the Awake Forced state to the Awake Free state, the OLT sends an SA(ON) message to the ONU. Meanwhile, the ONU in the Active Held state must wait for T_{hold} to expire, and an SA(ON) message from the OLT, in order to enter the Active Free state. Once

Table 6.3: Indications Activation Criteria for Scenarios 1, 2 and 3

Indication	Scenario 1	Scenario 2	Scenario 3
LWI	With a packet arrival	With a packet arrival	50 ms after a packet arrival
OLT-LWI	With a packet arrival	With a packet arrival	40 ms after a packet arrival
LDI, LSI and LPI	After 1.3 ms without a packet arrival	After 1.3 ms without a packet arrival	As soon as the queue at the ONU empties
!OLT-LWI	After 100 μs without a packet arrival	After 100 μs without a packet arrival	As soon as the queue at the OLT empties

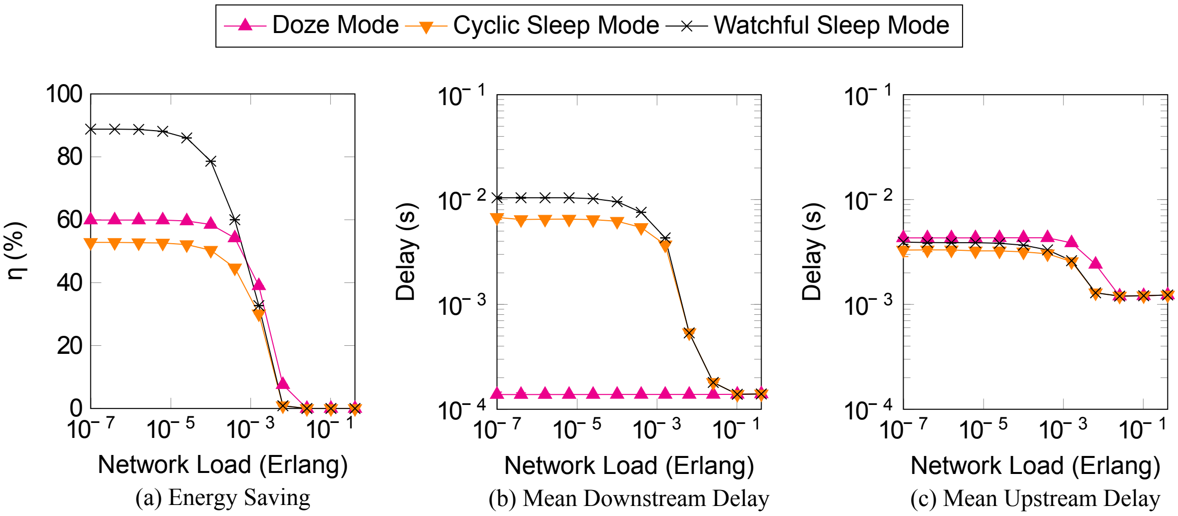
in the Active Free state, the ONU will verify when the last packet arrival occurred. If the last packet arrival was over 1.3 ms ago, the ONU will start a power saving phase; otherwise the ONU will wait until 1.3 ms from the last packet arrival. Once in a power saving phase, the ONU will alternate between the Aware state and the corresponding low power state until a packet arrival at the ONU or the OLT. Notice that, in order to start and maintain a power saving phase, it is necessary some time without any traffic in both downstream and upstream directions, which means that the ONU will not be able to save energy under intense traffic.



(a) Energy Saving (b) Mean Downstream Delay (c) Mean Upstream Delay

Figure 6.4: (a) Energy saving, (b) Mean Downstream delay and (c) Mean Upstream delay for the Cyclic Sleep, Doze and Watchful Sleep modes under Scenario 1.

In Scenarios 1 and 2, the three power management modes saves more energy for lower traffic loads (from 10^{-7} erlang to 10^{-4} erlang), and the Watchful Sleep mode outperforms the other two modes in energy efficiency. The energy saving under Scenarios 1

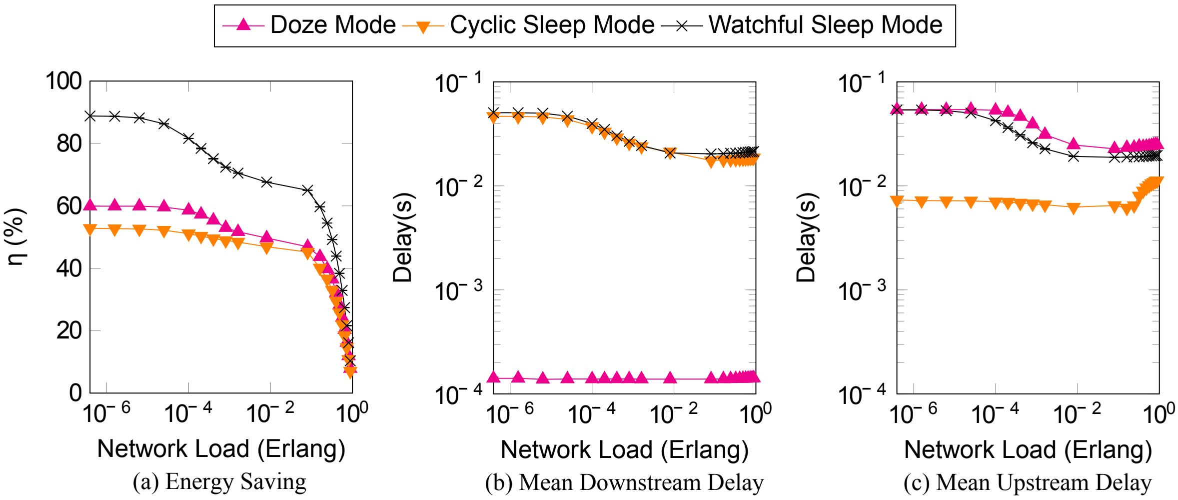


(a) Energy Saving
(b) Mean Downstream Delay
(c) Mean Upstream Delay

Figure 6.5: (a) Energy saving, (b) Mean Downstream delay and (c) Mean Upstream delay for the Cyclic Sleep, Doze and Watchful Sleep modes under Scenario 2.

is better than under Scenario 2 due to the higher values of T_{sleep} and T_{lowpower} used in Scenario 1 (see Tables 6.1 and 6.2). However, this increase in the T_{sleep} and T_{lowpower} parameters also results in a bigger mean downstream delay. The upstream delay is slightly bigger for Scenario 2, because T_{sleep} and T_{lowpower} does not influence the ONU-initiated wake up. The parameters responsible for this increase are T_{Rxinit}, T_{Txinit} and $T_{\text{Transinit}}$.

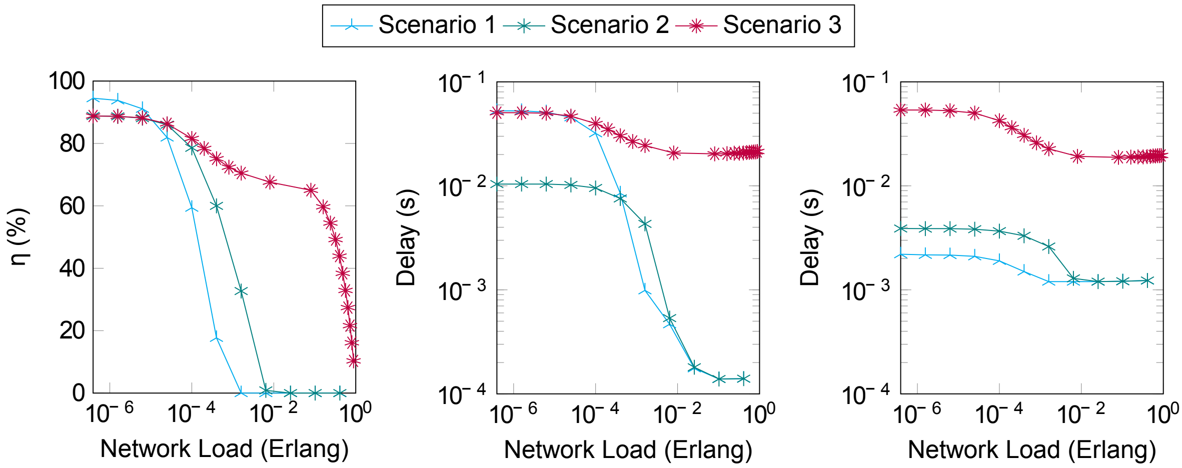
Figure 6.6 shows the energy saving, mean downstream delay, mean upstream delay, maximum downstream delay and maximum upstream delay for the three power management modes under Scenario 3. In Scenario 3, the OLT in the Awake Forced state enters the Awake Free state and, consequently, sends an SA(ON) message to the ONU, as soon as there are no packets for the target ONU in the queue. Meanwhile, the ONU in the Active Held state waits until T_{hold} expires and for the arrival of an SA(ON) message from the OLT, in order to enter the Active Free state. Once in the Active Free state, the ONU will verify if there is any packet in the queue. If the queue is empty, the ONU will start a power saving phase, otherwise, the ONU will wait until the queue empties to enter a power saving phase. The power saving phase will only be terminated 40 ms after a packet arrival at the OLT or after 50 ms after a packet arrival at the ONU. By making the ONU wait at least 40 ms before leaving a power saving phase, and allowing a power saving phase to start as long as the OLT and the ONU are able to empty their queues. Scenario 3 allows the ONU to save power even under intense traffic as long as the OLT and the ONU are capable of emptying their queues.



(a) Energy Saving (b) Mean Downstream Delay (c) Mean Upstream Delay

Figure 6.6: (a) Energy saving, (b) Mean Downstream delay and (c) Mean Upstream delay for the Cyclic Sleep, Doze and Watchful Sleep modes under Scenario 3.

The energy saving for the three power management modes under Scenario 3 is, for lower loads, very similar to the energy saving under Scenarios 1 and 2; and for higher loads, very different from Scenarios 1 and 2, since there is still some energy saving. For all three modes, the ONU is still able to maintain an energy saving bigger than 40% for loads close to 0.1 erlang, whereas for in Scenarios 1 and 2, the energy saving is 0% for loads greater than 0.01 erlang. This increase in energy efficiency also increased the downstream and upstream delays, however, the maximum delay in both downstream and upstream directions never surpass 56 ms. Appendix A presents a table with delay requirements from the ITU-T Recommendation G.1010 [40], where the delay requirements for delay sensitive applications, such as videophone and conversational voice, is 150 ms, which means that the 56 ms maximum delay is an acceptable delay. Figure 6.7 shows a comparison of the Watchful Sleep mode performance under Scenarios 1, 2 and 3.



(a) Energy Saving (b) Mean Downstream Delay (c) Mean Upstream Delay

Figure 6.7: (a) Energy saving, (b) Mean Downstream delay and (c) Mean Upstream delay for the Watchful Sleep mode under Scenarios 1, 2 and 3.

6.4 Simulation Results for TWDM-PON systems

The simulated network is a TWDM-PON with 4 wavelength pairs, each one with 16 ONUs, resulting in 64 ONUs. Each wavelength pair has a 10 Gb/s downstream and a 2.5 Gb/s upstream rate. Since one of the requirements for the NG-PON2 is a reach of at least 40 km, we assumed that every ONU is 40 km away from the OLT, resulting in a propagation delay of 200 μs. The duration of the TDM cycle is set to 2ms. Static bandwidth allocation is used. Every simulation was repeated 5 times.

Table 6.4: Parameter set for Scenarios 4 and 5

Parameter	Watchful Sleep Mode	Doze Mode	Cyclic Sleep Mode
T_{lowpower} (s)	10	–	–
T_{aware} (ms)	5	5	5
P_{aware} (%)	100	100	100
P_{listen}(%)	40	40	–
P_{asleep} (%)	5	–	5
T_{Txinit} (ms)	3	3	–
T_{Rxinit} (ms)	2	–	–
$T_{\text{Transinit}}$ (ms)	3	–	3

In Scenario 4, the !OLT-LWI, is activated after 100 μs without any packet arrival, whereas LSI, LDI and LPI are activated after 1.3 ms without any packet arrival. The OLT-LWI and LWI are activated with the arrival of a packet. In Scenario 5, differently from Scenario 4, the ONU activates !OLT-LWI, LSI, LDI and LPI as soon as the correspondent queue empties. The OLT-LWI and LWI are activated only 10 ms after

Table 6.5: Indications Activation Criteria for Scenarios 4 and 5

Indication	Scenario 4	Scenario 5
LWI & OLT-LWI	With a packet arrival	10 ms after a packet arrival
LDI, LSI and LPI	After 1.3 ms without a packet arrival	As soon as the queue at the ONU empties
!OLT-LWI	After 100 μs without a packet arrival	As soon as the queue at the OLT empties

the a packet arrival. Table 6.5 summarizes the indications activation criteria. All the results pertaining TWDM-PON systems are presented as a functions of the network load and $\mathrm{T_{sleep}}$.

In Scenario 4, similarly to Scenarios 1 and 2, the OLT in the Awake Forced state must wait for 100 μs without any packet arrival in order to enter the Awake Free state, and upon the transition from the Awake Forced state to the Awake Free state, the OLT sends an SA(ON) message to the ONU. Meanwhile, the ONU in the Active Held state must wait for $\mathrm{T_{hold}}$ to expire, and an SA(ON) message from the OLT, in order to enter the Active Free state. Once in the Active Free state, the ONU will verify when the last packet arrival occurred. If the last packet arrival was over 1.3 ms ago, the ONU will start a power saving phase; otherwise the ONU will wait until 1.3 ms from the last packet arrival. Once in a power saving phase, the ONU will alternate between the Aware state and the corresponding low power state until a packet arrival at the ONU or the OLT. Notice that, in order to start and maintain a power saving phase, it is necessary some time without any traffic in both downstream and upstream directions, which means that the ONU will not be able to save energy under intense traffic.

As expected, the energy saving for the Cyclic Sleep, Doze and Watchful Sleep modes under Scenario 4 (Figures 6.8, 6.9 and 6.10) is very promising for lower loads (from 10^{-7} erlang to 10^{-4} erlang), peaking in the lowest simulated load (around $2.5 \cdot 10^{-5}$ erlang) for $\mathrm{T_{sleep}} = 100$ ms at almost 90% of energy saving, for the Cyclic Sleep mode; over 50% of energy saving, for the Doze mode; and over 90% of energy saving for the Watchful Sleep mode. However, for loads between 0.01 erlang and 1 erlang the energy saving is practically negligible, due to the low packet inter-arrival time.

Besides the loads, a key parameter in the ONU energy saving is $\mathrm{T_{sleep}}$, which, differently from the loads, is a configurable parameter. There are many different opinions on an optimum value for $\mathrm{T_{sleep}}$ in the Cyclic Sleep mode. In [13], the author suggests a sleep

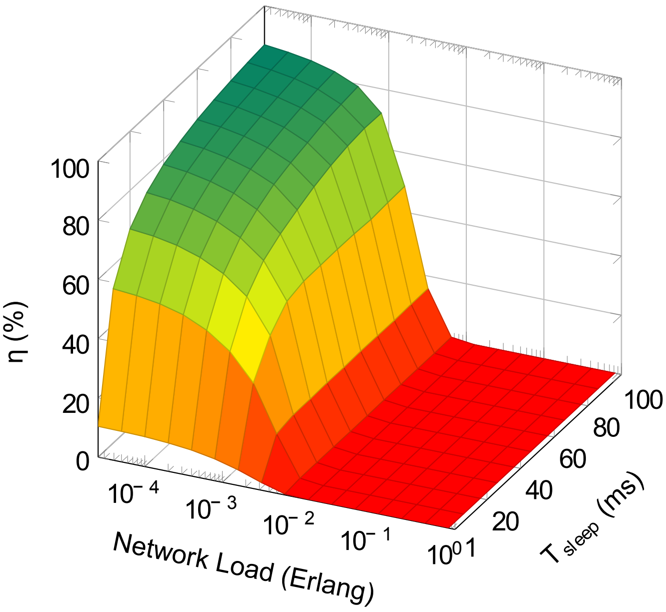


Figure 6.8: Energy Saving for the Cyclic Sleep mode under Scenario 4.

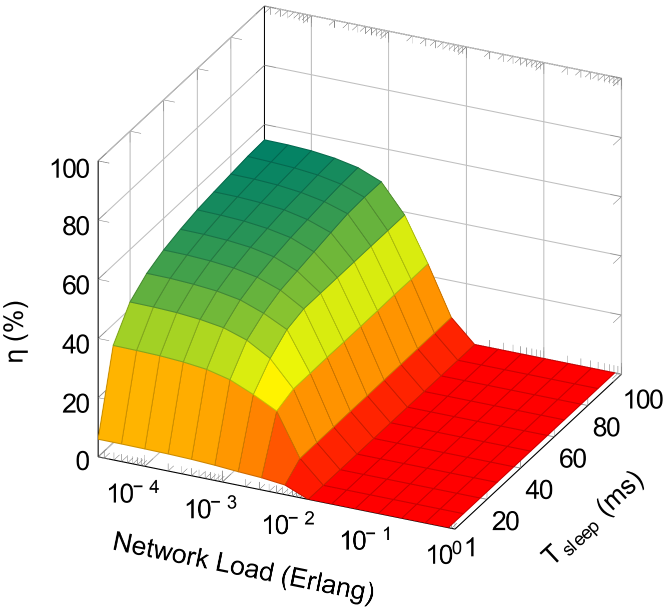


Figure 6.9: Energy Saving for the Doze mode under Scenario 4.

cycle within the range 10 ms – 100 ms, whereas in [41] the authors investigated an optimum value for T_{sleep} and concluded that, even though the energy saving rapidly increased until 50 ms, no prominent energy saving was found beyond that. Meanwhile, the report [18] indicates sleep periods of 20 ms – 50 ms for an effective energy saving.

In Figures 6.8, 6.9 and 6.10 it is easy to notice why no one recommends values bellow 10 ms for T_{sleep}. For both the Cyclic Sleep mode and the Doze mode, the energy saving for $T_{\mathrm{sleep}} = 1$ ms is insignificant when compared to the energy saving for T_{sleep} values

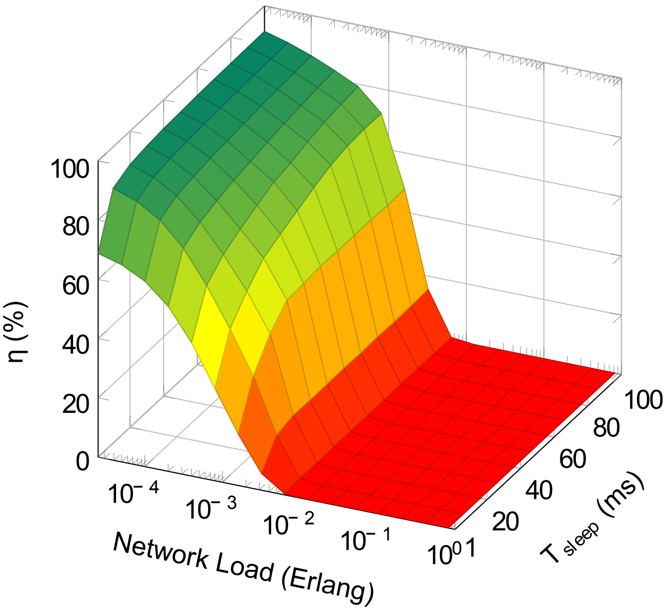


Figure 6.10: Energy Saving for the Watchful Sleep mode under Scenario 4.

above 10 ms. For the Watchful Sleep mode there is an energy saving of almost 70% for T_{sleep} = 1 ms, which is significantly smaller than the energy saving obtained for bigger T_{sleep} values. As for the claim that there is no substantial gain in the energy saving for $T_{\text{sleep}} > 50$ ms, it depends on the network load. For the lowest simulated load, the difference in the energy saving between $T_{\text{sleep}} = 50$ ms and $T_{\text{sleep}} = 100$ ms is approximately 6% for the Cyclic Sleep mode, approximately 4% for the Doze mode and less than 1% for the Watchful Sleep mode. This difference is almost constant for network loads bellow 0.001 erlang. After that load, the difference in the energy saving between $T_{\text{sleep}} = 50$ ms and $T_{\text{sleep}} = 100$ ms suddenly disappears. However, that does not change the fact that, for lower loads, the bigger T_{sleep} value is, the better the energy efficiency will be.

Figure 6.17 (a) shows the energy saving for the three power management modes with a network load of $2.5 \cdot 10^{-5}$ erlang. Notice that the Watchful Sleep mode is able to achieve an energy saving of almost 70% with T_{sleep} = 1 ms. This is an impressive result, specially considering that for the Doze mode, even if the ONU spent 100% of the time in the Listen state, the ONU would only be able to achieve 60% of energy saving, because of the P_{listen} value. Moreover, for the lowest simulated load with T_{sleep} = 10 ms, the Watchful Sleep mode was able to save as much energy as the Cyclic Sleep mode for the same load with T_{sleep} = 100 ms. With T_{sleep} = 100 ms, the energy saving for the Watchful Sleep mode is over 90% for the the lowest simulated load. However, as the network load increases, the difference in the energy saving between the Cyclic

Sleep and Watchful Sleep mode decreases until 0.0002 erlang, when both modes start having the same energy saving. In this load (0.0002 erlang), the average packet inter-arrival time is probably smaller than $T_{\text{aware}} + T_{\text{sleep}}$, which results on the power saving phase being terminated before the first T_{sleep} expires event, resulting on the equivalent of a scenario were $T_{\text{lowpower}} \leq T_{\text{sleep}}$. Under this condition, the Watchful Sleep mode emulates the Cyclic Sleep mode.

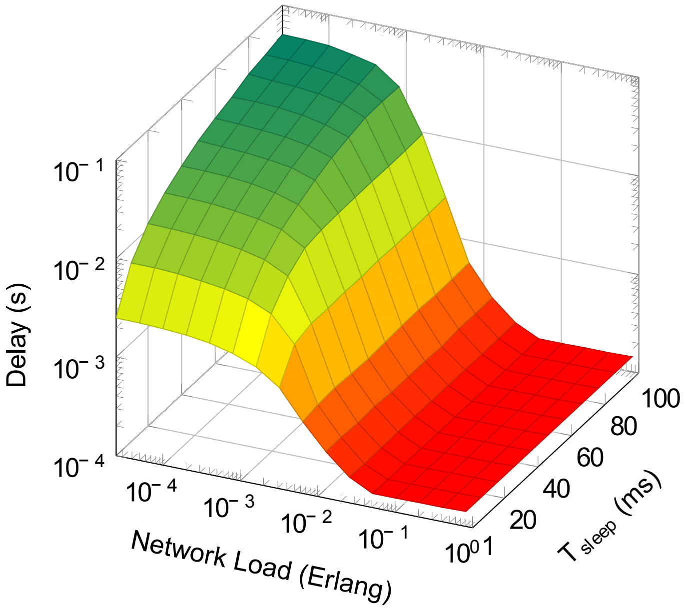


Figure 6.11: Mean downstream delay for the Cyclic Sleep mode under Scenario 4.

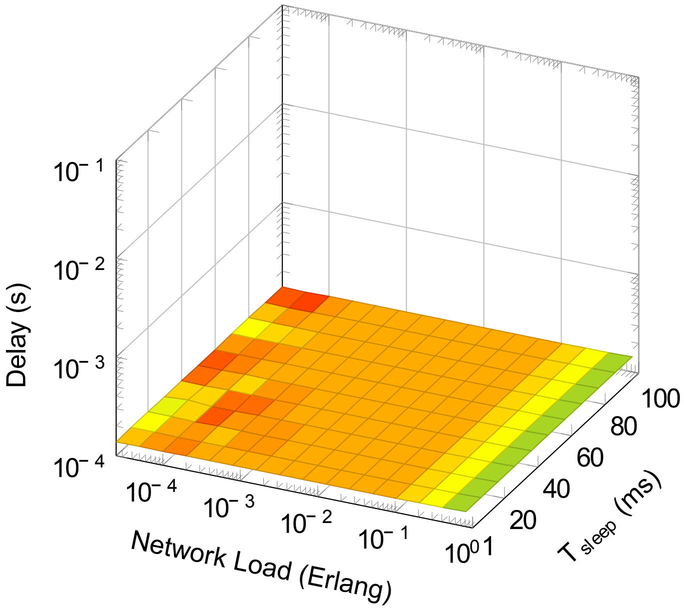


Figure 6.12: Mean downstream delay for the Doze mode under Scenario 4.

The major constraint in choosing a big T_{sleep} value is the impact that it will have on the end-to-end delay. Figures 6.11, 6.12 and 6.13 shows the mean delay in the downstream

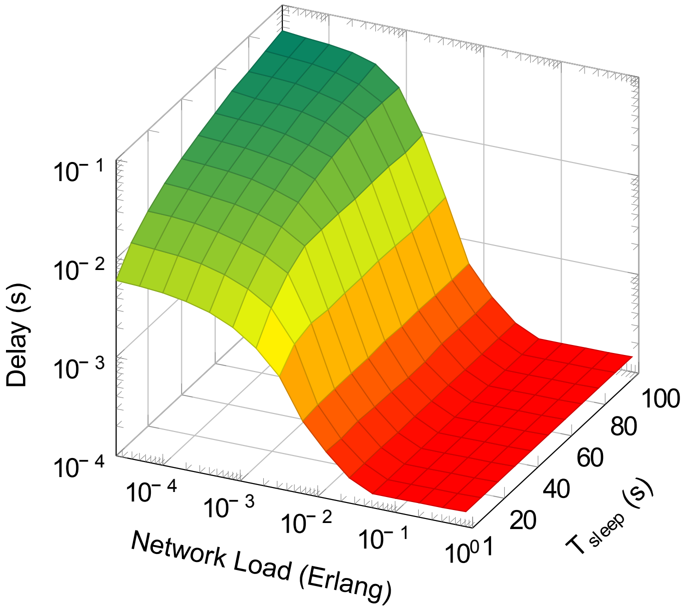


Figure 6.13: Mean downstream delay for the Watchful Sleep mode under Scenario 4.

direction for the Cyclic Sleep, Doze and watchful Sleep modes under Scenario 4. While the mean downstream delay for the Cyclic Sleep and Watchful Sleep modes have a very similar shape to the energy saving result, the mean downstream delay for the Doze mode is constant, regardless of T_{sleep} and the considered loads. Since the ONU maintains the receiver always `ON`, there is no need for the OLT to buffer the downstream traffic, which results on the Doze mode not having any effect on the downstream delay. Therefore, even though the Doze mode cannot save as much energy as the Cyclic Sleep and Watchful Sleep modes, it has no impact on the downstream delay, thus, T_{sleep} can be as big as possible for the Doze mode. On the other hand, T_{sleep} has a large impact on the downstream delay for the Cyclic Sleep and Watchful Sleep modes, specially for lower loads. For $T_{\text{sleep}} = 100$ ms and the lowest simulated load, the mean downstream delay is approximately 50 ms for the Cyclic Sleep and Watchful Sleep modes. The increase in the downstream delay for the Cyclic Sleep mode with $T_{\text{sleep}} = 1$ ms is large when compared to the energy efficiency gain (a 2 ms increase in the mean delay for approximately 5% of energy saving). This is due to the $T_{\text{Transinit}}$ value. During the transceiver initialization, the simulations considered the power consumption as 100% and that the ONU was with both receiver and transmitter `OFF`. Thus, by having a T_{sleep} much smaller than $T_{\text{Transinit}}$ value, the $T_{\text{sleep}} = 1$ ms case has a much worse trade-off between energy efficiency and downstream delay than the other T_{sleep} simulated values. It is also worth noticing that, there are loads where there is an increase in the delay, but without any energy saving (around 0.01 erlang and 0.05 erlang). In this interval, the ONU was able to start a power saving phase, however, it could not maintain it until the transition to the Asleep state. The downstream delay for the Watchful Sleep mode is almost the same as the downstream delay for the Cyclic Sleep mode, which means that the Watchful Sleep mode can save more energy than the Cyclic Sleep mode, while maintaining almost the same delay. The mean downstream delay is, however, slightly smaller for the Cyclic Sleep mode, because in the Cyclic Sleep mode the ONU spends more time in the Aware state than in the Asleep state, increasing the probability that the packet arrival will occur during the Aware state. If not for that, both modes would have practically the same downstream delay. This difference is, for the lowest simulated load, around 4 ms for every value of T_{sleep}, and it disappears for higher loads. Figure 6.17 (b) shows the mean downstream delay for the three power management modes for the lowest simulated load.

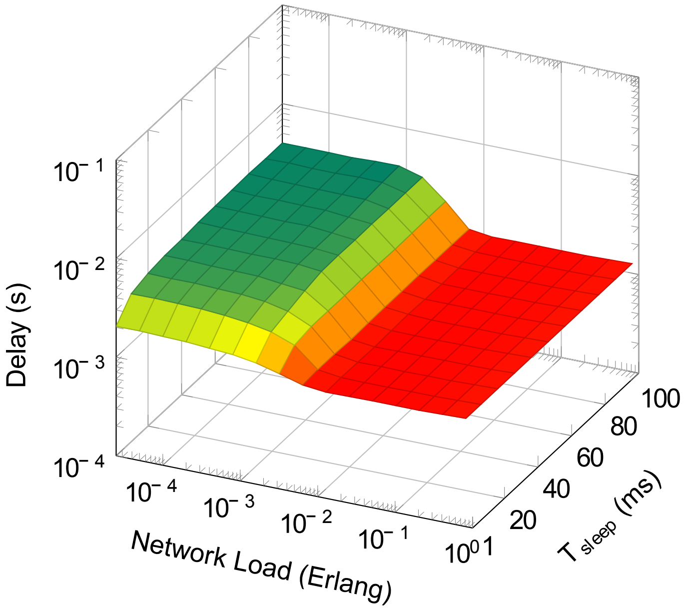


Figure 6.14: Mean upstream delay for the Cyclic Sleep mode under Scenario 4.

Figures 6.14, 6.15 and 6.16 show the mean delay in the upstream direction for the Cyclic Sleep, Doze and Watchful Sleep modes. For the parameters configured in Scenario 4, when an upstream packet arrives at the ONU, the ONU will simply transit to the Active Held state, and then send the packet as soon as possible, that is, T_{sleep} has no influence in the upstream delay. The increase in the upstream delay is caused by: $T_{\text{Transinit}}$, for the Cyclic Sleep mode; T_{Txinit}, for the Doze mode; and T_{Rxinit}, T_{Txinit} and $T_{\text{Transinit}}$ for the watchful Sleep mode. Since these $T_{\text{Transinit}}$ and T_{Txinit} values are set to 3 ms, and T_{Rxinit} is set to 2 ms (see Table 6.4), the results for the mean upstream delay for the three modes are almost identical. The mean upstream delay is smaller for T_{sleep} = 1 ms, because the ONU spends more time in the Aware state, which increases the probability of a packet arriving when the ONU is already in a full power state. Figure

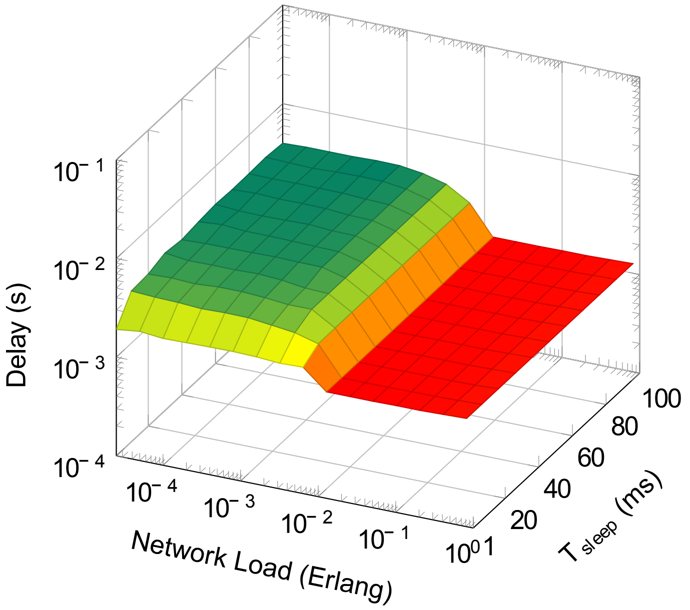


Figure 6.15: Mean upstream delay for the Doze mode under Scenario 4.

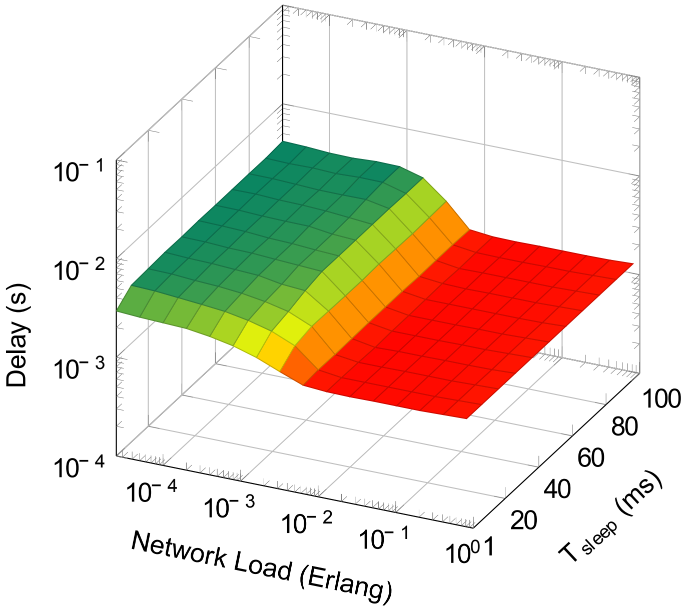
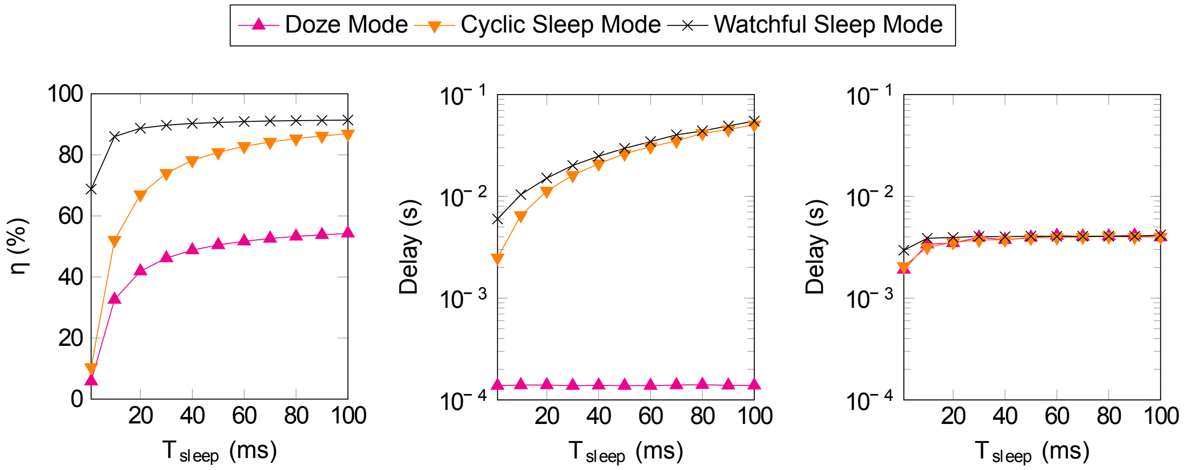


Figure 6.16: Mean upstream delay for the Watchful Sleep mode under Scenario 4.

6.17 (c) shows the mean upstream delay for the three power management modes for the lowest simulated load.

Even though Scenario 4 showed very promising results for lower loads, under intense traffic the ONU barely saved any energy. Scenario 4 prioritizes the network performance over the energy efficiency, while still managing to save some energy during periods of inactivity.



(a) Energy Saving (b) Mean Downstream Delay (c) Mean Upstream Delay

Figure 6.17: (a) Energy Saving, (b) Mean Downstream Delay and (c) Mean Upstream Delay against T_{sleep} for the Cyclic Sleep, Doze and Watchful Sleep modes under Scenario 4 with a network load of $2.5 \cdot 10^{-5}$ erlang.

In Scenario 5, the OLT in the Awake Forced state enters the Awake Free state and, consequently, sends an SA(ON) message to the ONU, as soon as there are no packets for the target ONU in the queue. Meanwhile, the ONU in the Active Held state waits until T_{hold} expires and for the arrival of an SA(ON) message from the OLT, in order to enter the Active Free state. Once in the Active Free state, the ONU will verify if there is any packet in the queue. If the queue is empty, the ONU will start a power saving phase, otherwise, the ONU will wait until the queue empties to enter a power saving phase. The power saving phase will only be terminated 10 ms after a packet arrival at the OLT or at the ONU. By making the ONU wait at least 10 ms before leaving a power saving phase, and allowing a power saving phase to start as long as the OLT and the ONU are able to empty their queues. Scenario 5 allows the ONU to save power even under intense traffic as long as the OLT and the ONU are capable of emptying their queues.

The energy saving for the Cyclic Sleep, Doze and Watchful Sleep modes under Scenario 5 (see Figures 6.18, 6.19 and 6.20) is, for lower loads, very similar to the energy saving under Scenario 4; and for higher loads, very different from Scenario 4, since there is still some energy saving. For the Cyclic Sleep and Watchful Sleep modes, the ONU is still able to maintain an energy saving bigger than 20% for loads close to 0.5 erlang, whereas for the Doze mode, the energy saving is almost 20%. These values are only valid when considering $T_{\text{sleep}} \geq 10$ ms. For $T_{\text{sleep}} = 1$ ms the energy saving is approximately 5% in the highest simulated load for the Cyclic Sleep and Doze modes, whereas for the Watchful Sleep mode the energy saving is over 10% for $T_{\text{sleep}} = 1$ ms in the highest simulated load. For higher loads, where Scenario 4 was unable to save any energy, the

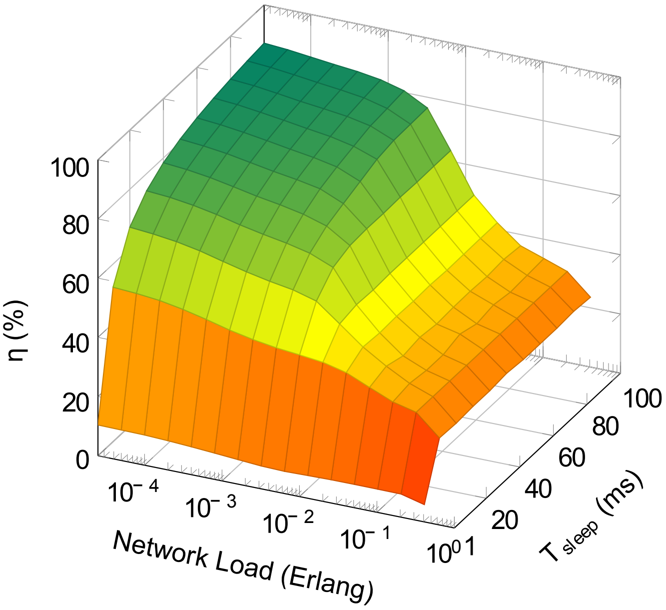


Figure 6.18: Energy Saving for the Cyclic Sleep mode under Scenario 5.

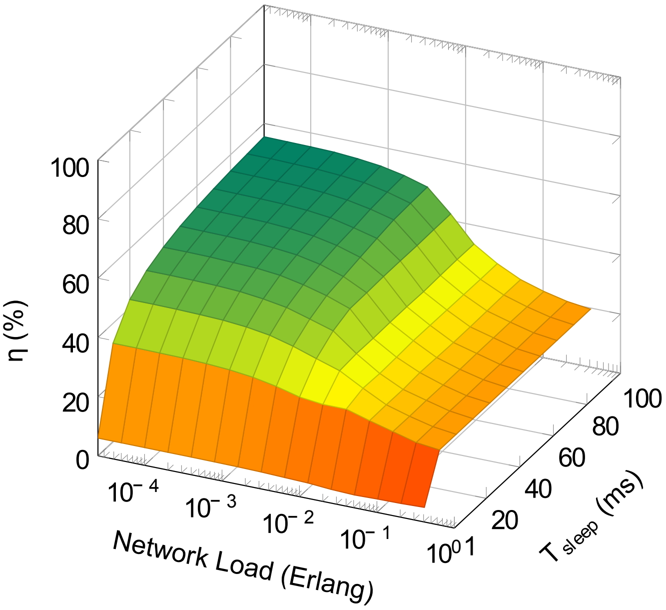


Figure 6.19: Energy Saving for the Doze mode under Scenario 5.

ONU under Scenario 4 was forced to leave the power saving phase even before entering a low power state, if it was able to initiate a power saving phase at all. By forcing the ONU to delay the wake-up process in 10 ms, the ONU can maintain a power saving phase long enough to enter into a low power state. Assuming that a packet arrived as soon as the ONU started the power saving phase, then, the sojourn in the low power state will be only 5 ms. For $\mathrm{T_{sleep}} > 5$ ms, the ONU will terminate the power saving phase before the first $\mathrm{T_{sleep}}$ expires event, resulting on the equivalent of a scenario were $\mathrm{T_{lowpower}} \leq \mathrm{T_{sleep}} \leq 5$ ms. Under this condition, the Watchful Sleep mode emulates the

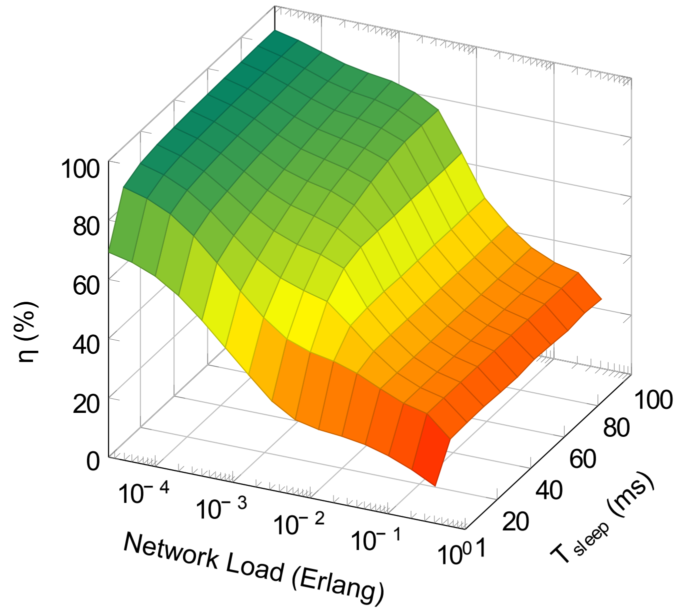


Figure 6.20: Energy Saving for the Watchful Sleep mode under Scenario 5.

Cyclic Sleep mode.

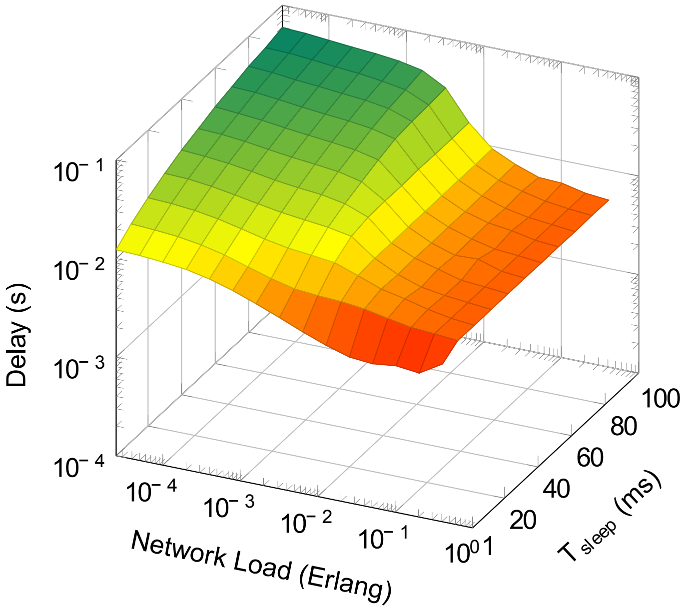


Figure 6.21: Mean downstream delay for the Cyclic Sleep mode under Scenario 5.

The mean downstream delay for the Cyclic Sleep and Watchful Sleep modes under Scenario 5 (see Figures 6.21 and 6.21) is, for lower and higher loads, 5 ms–10 ms bigger than under Scenario 4. For loads between 0.00005 erlang and 0.005 erlang, this difference varies between 5 ms and 30 ms. Figure 6.27 (b) shows the mean downstream delay for the three power management modes under Scenario 5 for the lowest simulated network load. The mean downstream for the Watchful Sleep mode under Scenario 5, is slightly bigger than the mean downstream delay for the Cyclic Sleep mode. For lower

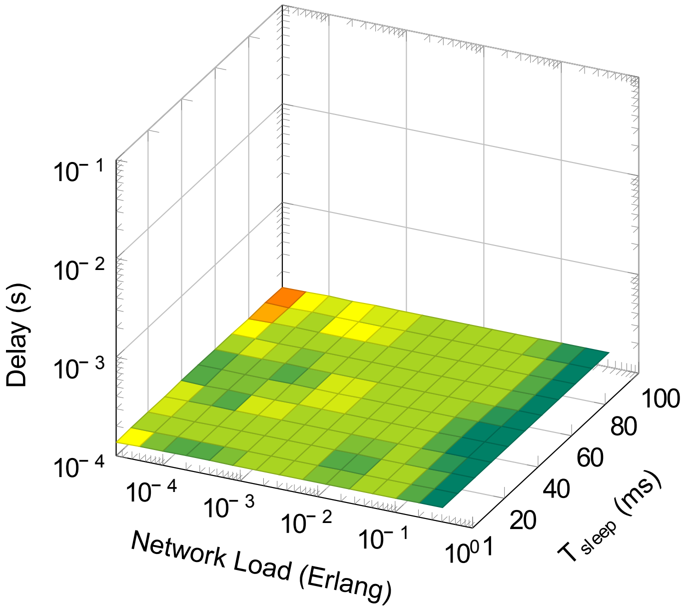


Figure 6.22: Mean downstream delay for the Doze mode under Scenario 5.

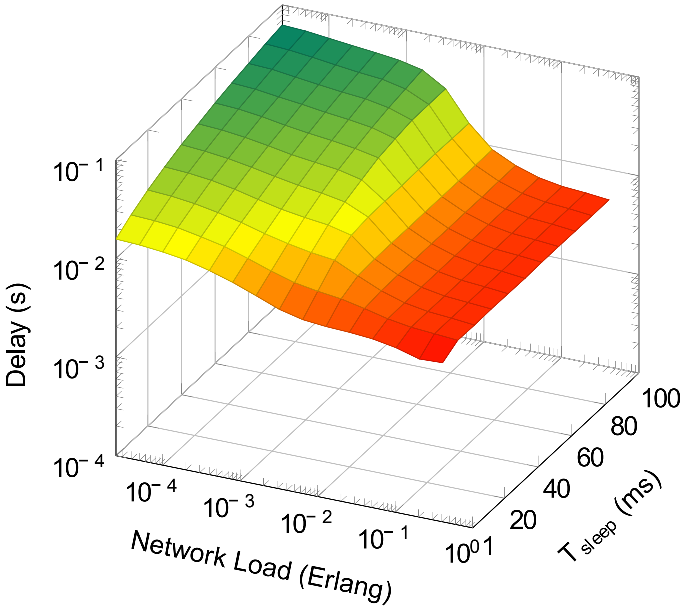


Figure 6.23: Mean downstream delay for the Watchful Sleep mode under Scenario 5.

loads, the difference between the mean downstream delay for the Watchful Sleep mode and the Cyclic Sleep mode varies between 1 ms and 3 ms. The mean downstream delay for the Doze mode under Scenario 5 (see Figure 6.21) is, just like under Scenario 4, constant.

The mean upstream delay for the Cyclic Sleep, Doze and Watchful Sleep modes under Scenario 5 (see Figures 6.24, 6.25 and 6.26) is, for every simulated load, 1ms – 10ms bigger than under Scenario 4. Even for the lowest loads, the mean upstream delay is

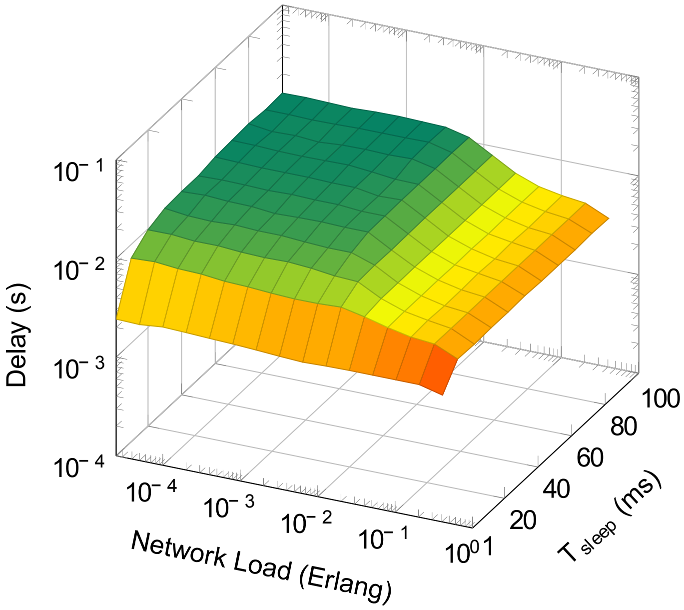


Figure 6.24: Mean upstream delay for the Cyclic Sleep mode under Scenario 5.

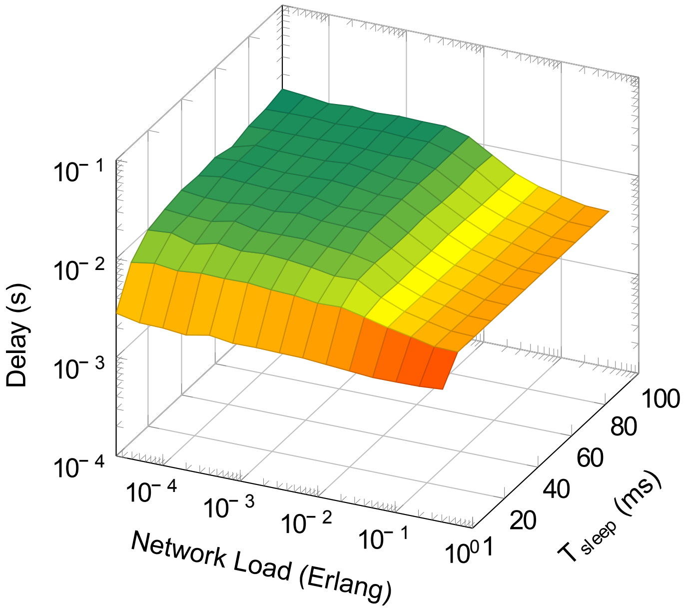


Figure 6.25: Mean upstream delay for the Doze mode under Scenario 5.

increased in a few ms. The upstream delay results for the three power management modes are very similar. Figure 6.27 (c) shows the mean upstream delay for the three power management modes under Scenario 5 for the lowest simulated network load.

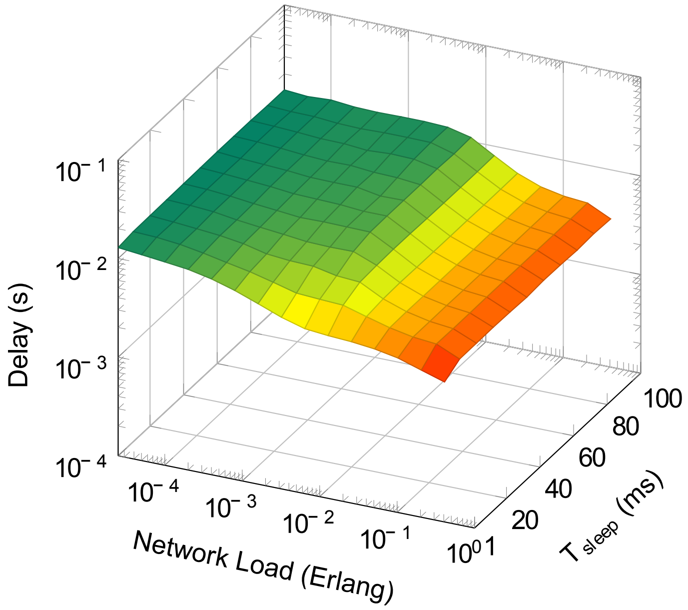
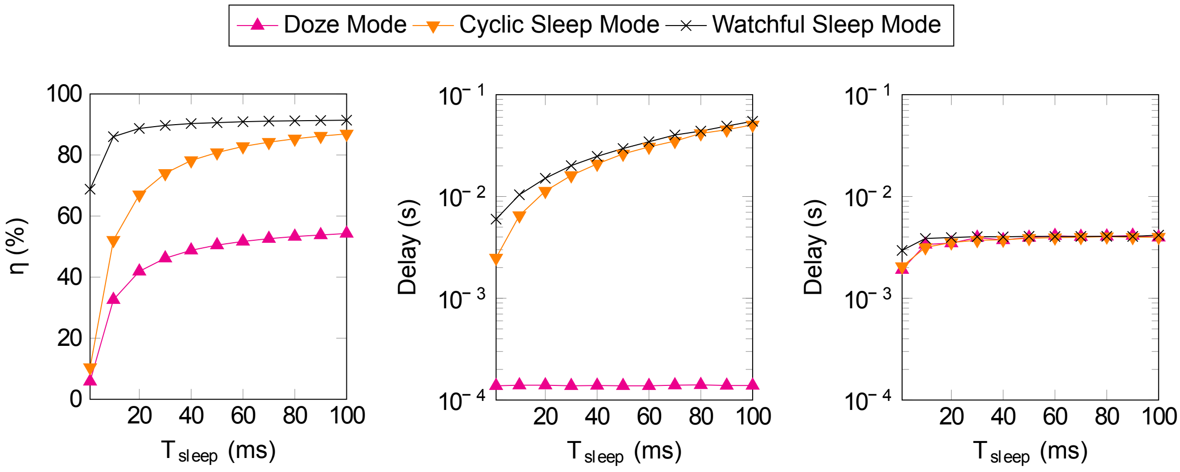


Figure 6.26: Mean upstream delay for the Watchful Sleep mode under Scenario 5.



(a) Energy Saving

(b) Mean Downstream Delay

(c) Mean Upstream Delay

Figure 6.27: (a) Energy Saving, (b) Mean Downstream Delay and (c) Mean Upstream Delay against T_{sleep} for the Cyclic Sleep, Doze and Watchful Sleep modes under Scenario 5 with a network load of $2.5 \cdot 10^{-5}$ erlang.

Scenario 5 saved energy with the three power management modes even for higher loads. However, the 10 ms waiting time was just too small to achieve any significant amount of energy saving. By increasing the waiting time, it would be possible to save more energy, however, it would also increase the delay in both directions.

Chapter 7 Conclusions

Energy efficiency has become an increasingly important aspect of access network design. In order to address the energy efficiency issue in TDM-PON systems, the ITU-T standardized two power management modes: the Cyclic Sleep mode and the Doze mode. However, there is no technical reason to maintain separation between the Cyclic Sleep mode and the Doze mode. In fact, the separation of the two power management modes reduces the ONU energy efficiency once in a power saving phase.

In this dissertation, we presented the Watchful Sleep mode, a new mode which unifies the Cyclic Sleep and Doze modes into a single power management mode. The Watchful Sleep mode simplifies the implementation of the power management techniques at the ONU and OLT, and also combines the advantages of the Cyclic Sleep and Doze modes, outperforming either of them. Moreover, a PON system supporting the Watchful Sleep mode can also emulate the Cyclic Sleep mode or the Doze mode as a special case. Due to its effectiveness, implementation simplicity, and maximum energy efficiency, the Watchful Sleep mode has been approved to be included in the ITU-T G.984 (G-PON) and ITU-T G.987 (XG-PON) standards. It is expected to be the default technique for power management operations for ONUs in next-generation PONs.

The results presented in this work show the performance of three protocol-based power management mechanisms on XG-PON and TWDM-PON systems: The Cyclic Sleep mode, the Doze mode and the Watchful Sleep mode. The five analyzed scenarios showed very distinct behaviors. Scenarios 1, 2 and 4 presented very promising results for lower loads, however they were unable of saving energy for higher loads. These scenarios seems to be adequate when prioritizing network performance over energy efficiency, since, apparently it only saves energy when the user is away, having practically no effect on the end-user experience. On the other hand, Scenarios 3 and 5 were more balanced, as it was capable of saving energy even for higher loads, while maintaining the mean delay for both downstream and upstream directions bellow 56 ms for these loads. These five scenarios show how flexible the three power management modes can be. Appendix A presents some delay requirements, where the maximum delay requirement for voice traffic is 150 ms, and for video it is 250 ms. None of the delays presented in this work surpassed these delays requirements.

The results presented in this work are based on simple implementations, and more research on the Watchful Sleep mode can be expected in the future. The implementation of the local indications, which determines the start and the end of a power saving phase, has a great influence on the simulations results and requires further research. The determination of an optimum value for the $\mathrm{T}_{\mathrm{sleep}}$ and $\mathrm{T}_{\mathrm{lowpower}}$ parameters should be pursued in future researches.

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APPENDICES

Appendix A Delay Requirements

In this work, the performance of the power management modes were analyzed using the energy saving, mean upstream and mean downstream delays as performance measures. To establish what is an acceptable delay, the ITU-T Recommendation G.1010 [40] on the End-used multimedia QoS categories was consulted. This recommendation presents some delay requirements for audio, video and data applications. The following table (Table A.1) was obtained in this recommendation.

Table A.1: Performance targets for audio, video and data applications.

Medium	Application	Typical data rates	One-way delay
Audio	Conversational voice	4–64 kbit/s	Preferred: $<$ 150 ms Limit: $<$ 400 ms
Audio	Voice messaging	4–32 kbit/s	$<$ 1 s for playback $<$ 2 s for record
Audio	High quality streaming audio	16–128 kbit/s	$<$ 10 s
Video	Videophone	16–384 kbit/s	Preferred: $<$ 150 ms Limit: $<$ 400 ms
Video	One-way	16–384 kbit/s	$<$ 10 s
Data	Web-browsing – HTML	$\sim$ 10 KB	Preferred: $<$ 2 s/page Acceptable: $<$ 4 s/page
Data	Bulk data transfer/retrieval	10KB–10MB	Preferred: $<$ 15 s Acceptable: $<$ 4 s
Data	Transaction services – high priority e.g. e-commerce, ATM	$<$ 10 KB	Preferred: $<$ 2 s Acceptable: $<$ 4 s
Data	Command/control	$\sim$ 1 KB	$<$ 250 ms
Data	Still image	$<$ 100 KB	Preferred: $<$ 15 s Acceptable: $<$ 60 s

Medium	Application	Typical data rates	One-way delay
Data	Interactive games	< 1 KB	< 200 ms
Data	Telnet	< 1 KB	< 200 ms
Data	E-mail (server to access)	< 10 KB	Preferred: < 2 s Acceptable: < 4 s
Data	E-mail (server to serve transfer)	< 10 KB	Can be several minutes
Data	Fax ("real-time")	10 KB	< 30 s/page
Data	Fax (store & forward)	~ 10 KB	Can be several minutes
Data	Low priority transactions	< 10 KB	< 30 s
Data	Usenet	Can be 1 MB or more	Can be several minutes

Appendix B PLOAM Messages

B.1 XG-PON PLOAM Messages

The PLOAM messaging channel is based on a fixed set of messages transported on the XGTC frame header (downstream) and the XGTC burst header (upstream). It is used for low-level negotiations between OLT and ONU, such as power management operations. The PLOAM message in XG-PON system are always 48 bytes long. Every PLOAM message has the same structure shown in Table B.1.

Table B.1: PLOAM message structure

Octet	Field	Description
1–2	ONU-ID	The six most significant bits are `0` padding. The next ten bits are occupied by the ONU-ID.
3	Message Type ID	Indicates the message type.
4	SeqNo	Sequence number.
5 – 40	Message_Content	Depends on the message type.
41 – 48	MIC	Message integrity check.

B.1.1 Downstream PLOAM messages

B.1.1.1 Profile message

The Profile message is a broadcast/unicast message to provide upstream burst header information sent periodically by the OLT. The ONU stores the profile for use in subsequent upstream transmissions.

Table B.2: Profile Message

Octet	Content	Description
1–2	ONU-ID	May be an unicast message to one ONU, or a broadcast message to all ONUs. To broadcast for all ONUs, ONU-ID = `0x03FF`.
3	`0x01`	Message type ID for Profile message

Octet	Content	Description
4	SeqNo	Sequence number.
5	`VVVV 00PP`	`VVVV`: Four-bit profile version. `PP`: Two-bit profile index.
6	`0000 000F`	`F` = 1: FEC on. `F` = 0: FEC off.
7	`0000 DDDD`	`DDDD`: Delimiter Length. Number of bits in the Delimiter field, in the range 0–8.
8 – 15	Delimiter	The Delimiter that will be used in the PSBu in a PHY burst (see Figure 3.4).
16	`0000 LLLL`	`LLLL`: Preamble Length. Number of bits in the Preamble field, in the range 1–8.
17	`000R RRRR`	`RRRRR`: Preamble Repeat Count, range 0–31. The number of times that the preamble sequence will be repeated.
18 – 25	Preamble	The Preamble pattern that will be used in the PSBu in a PHY burst.
26 – 33	PON-TAG	8-byte static identity used in the initial derivation of the master session key.
34 – 40	Padding	Set as `0x00`.
41 – 48	MIC	Message integrity check.

B.1.1.2 Assign_ONU-ID message

The Assign_ONU-ID message is a message the OLT sends to an ONU as a response to a Serial_Number_ONU message. It assigns an ONU-ID to the ONU with the same Vendor-ID and Vendor-Specific Serial Number (VSSN) from the message.

Table B.3: Assign ONU-ID Message

Octet	Content	Description
1–2	`0x03FF`	Broadcast.
3	`0x03`	Message type ID for Assign_ONU-ID message.
4	SeqNo	Sequence number.
5 – 6	ONU-ID	ONU-ID that will be assigned to the target ONU.
7 – 10	Vendor-ID	Vendor-ID from the target ONU. The Vendor-ID is a four character string.

Octet	Content	Description
11 – 14	VSSN	Vendor-Specific Serial Number from the target ONU.
15 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.1.3 Ranging_Time message

The Ranging_Time message indicates the round–trip equalization delay. It is sent when the OLT needs to update the equalization delay.

Table B.4: Ranging_Time Message

Octet	Content	Description
1–2	ONU-ID	May be an unicast message to one ONU, or a broadcast message to all ONUs. To broadcast for all ONUs, ONU-ID = `0x03FF`.
3	`0x04`	Message type ID for Ranging_Time message.
4	SeqNo	Sequence number.
5	`0000 00SP`	Indicates how the equalization delay is to be interpreted. Bit `P` = 1: The EqualizationDelay is an absolute value. Ignore `S`. Bit `P` = 0: The EqualizationDelay is relative. `S` determines the sign. Bit `S` = 0: The sign in positive. Increase the current equalization delay with the value in the EqualizationDelay field. Bit `P` = 1:The sign in negative. Decrease the current equalization delay with the value in the EqualizationDelay field.
6 – 9	EqualizationDelay	Equalization Delay value in 2.5 Gb/s bit times.
10 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.1.4 Deactivate_ONU-ID message

The Deactivate_ONU-ID message is sent to ONU, or all the ONUs, to stop sending upstream traffic and reset itself/themselves.

Table B.5: Deactivate_ONU-ID Message

Octet	Content	Description
1–2	ONU-ID	May be an unicast message to one ONU, or a broadcast message to all ONUs. To broadcast for all ONUs, ONU-ID = `0x03FF`.
3	`0x05`	Message type ID for Deactivate_ONU-ID message.
4	SeqNo	Sequence number.
5 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.1.5 Disable_Serial_Number message

The disable_Serial_Number message is a broadcast message to disable/enable the ONU with this Vendor-ID and VSSN.

Table B.6: Disable_Serial_Number Message

Octet	Content	Description
1–2	ONU-ID	Broadcast.
3	`0x06`	Message type ID for Disable_Serial_Number message.
4	SeqNo	Sequence number.
5	Disable/Enable	`0xFF`: The ONU with this Vendor ID code and VSSN is denied upstream access. `0x00`: The ONU with this Vendor ID code and VSSN is allowed upstream access. `0x0F`: All ONUs are denied upstream access. `0xF0`: All ONUs are allowed upstream access.
6 – 9	Vendor ID	Vendor-ID from the target ONU. The Vendor-ID is a four character string.
10 – 13	VSSN	Vendor-Specific Serial Number from the target ONU.

Octet	Content	Description
14 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.1.6 Request_Registration message

The Request_Registration message is sent to request an ONU registration IN. When the ONU receives this message, it sends the Registration message to the OLT.

Table B.7: Request_Registration Message

Octet	Content	Description
1–2	ONU-ID	Unicast.
3	`0x09`	Message type ID for Request_Registration message.
4	SeqNo	Sequence number.
5 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.1.7 Assign_Alloc-ID message

Assign_Alloc-ID message is sent in order to assign the specified Alloc-ID to an ONU.

Table B.8: Assign_Alloc-ID Message

Octet	Content	Description
1–2	ONU-ID	Unicast.
3	`0x0A`	Message type ID for Assign_Alloc-ID message.
4	SeqNo	Sequence number.
5 – 6	Alloc-ID-value	The Alloc-ID value is 14-bit long located in the least significant bits. The 2 most significant bits are set to `0`.
7	Alloc-ID-type ID	`1`: X-GEM encapsulated payload. `255`: Deallocate this Alloc-ID Other values: reserved.
8 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.1.8 Key_Control message

The Key_Control message is sent in order to instruct the ONU to generate of confirm a data encryption key.

Table B.9: Key_Control Message

Octet	Content	Description
1–2	ONU-ID	May be an unicast message to one ONU, or a broadcast message to all ONUs. To broadcast for all ONUs, ONU-ID = `0x03FF`.
3	`0x0D`	Message type ID for Key_Control message.
4	SeqNo	Sequence number.
5	Reserved	Set to `0x00`.
6	`0000 000C`	`C` = 0: The ONU shall **generate** a new key. `C` = 1: The ONU shall **confirm** an existing key by returning the hash of the key via the Key_Report message.
7	`0000 000b`	Key index. `bb` = `01`: First key. `bb` = `10`: Second key.
8	Key_Length	Specifies the key length in bytes.
9 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.1.9 Sleep_Allow message

The Sleep_Allow message is sent to enable or disable a power management mode in the ONU.

Table B.10: Sleep_Allow Message

Octet	Content	Description
1–2	ONU-ID	May be an unicast message to one ONU, or a broadcast message to all ONUs. To broadcast for all ONUs, ONU-ID = `0x03FF`.
3	`0x12`	Message type ID for Sleep_Allow message.
4	SeqNo	Sequence number.

Octet	Content	Description
5	`0000 000A`	`A` = `0`: SA(OFF). `A` = `1`: SA(ON).
6 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.2 Upstream PLOAM messages

B.1.2.1 Serial_Number_ONU message

The Serial_Number_ONU message is sent to report the serial number of the ONU.

Table B.11: Serial_Number_ONU Message

Octet	Content	Description
1–2	`0x03FF`	Unassigned ONU-ID.
3	`0x01`	Message type ID for Serial_Number_ONU message.
4	`0x00`	Sequence number.
5 – 8	Vendor-ID	A four character string that identifies the vendor.
9 – 12	VSSN	Vendor-Specific Serial Number.
13 – 16	Random_delay	The random delay used when sending this message. Measured in 2.5 Gb/s bit times.
17 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.2.2 Registration message

The Registration message is sent to report the registration ID of an ONU.

Table B.12: Registration Message

Octet	Content	Description
1–2	ONU-ID	Sender identity.
3	`0x02`	Message type ID for Registration message.
4	SeqNo	Sequence number.

Octet	Content	Description
5 – 40	Registratio_ID	A 36 octet string that may be used to identify a particular ONU.
41 – 48	MIC	Message integrity check.

B.1.2.3 Key_Report message

The Key_Report message is sent as a response for the Key_Control message. This message may contain a fragment of a new data encryption key or the hash of an existing data encryption key.

Table B.13: Key_Report Message

Octet	Content	Description
1–2	ONU-ID	Sender identity.
3	`0x05`	Message type ID for Registration message.
4	SeqNo	Sequence number.
5	`0000 000R`	Report type. `R` = `0`: Contains a newly generated key or key fragment. `R` = `1`: Contains the hash of an existing key.
6	`0000 00bb`	`bb` = `01`: First Key. `bb` = `10`: Second Key.
7	`0000 0FFF`	Fragment number, in the range 0–7.
8	Reserved	set to `0x00`.
9 – 40	Key_Fragment	The 32 bytes newly generated key fragment or the 16 bytes hash of the key to confirm an existing key.
41 – 48	MIC	Message integrity check.

B.1.2.4 Acknowledgement message

The Acknowledgement message is sent as a response for any downstream message that requires acknowledgement.

Table B.14: Acknowledgement Message

Octet	Content	Description
1–2	ONU-ID	Sender identity.
3	`0x09`	Message type ID for Acknowledgement message.
4	SeqNo	Sequence number.
5	Completion_code	`0`: OK. `1`: No message to send. `2`: Busy, preparing a response. `3`: Unknown message type. `4`: Parameter error. `5`: Processing error. Other values: Reserved.
6 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.

B.1.2.5 Sleep_Request message

The Sleep_Request message is sent to signal that the ONU will start or terminate a power saving phase.

Table B.15: Sleep_Request Message

Octet	Content	Description
1–2	ONU-ID	Sender identity.
3	`0x10`	Message type ID for Acknowledgement message.
4	SeqNo	Sequence number.
5	Activity_level	`0`: Sleep_Request(Awake) `1`: Sleep_Request(Doze) `2`: Sleep_Request(Sleep) `3`: Sleep_Request(WSleep) Other values: Reserved
6 – 40	Padding	Set to `0x00`.
41 – 48	MIC	Message integrity check.