A Mathematical Model for a GA-Based Dynamic Excess Bandwidth Allocation Algorithm for Hybrid PON and Wireless Technology Integrations for Next Generation Broadband Access Networks

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***Abstract*—Optical and wireless integration scheme merges the high-speed and high-capacity of the optical networks with the low-cost, wide-coverage and mobility features of the wireless counterparts for the Subscriber Stations (SSs). It is also financially viable for the telecommunication service providers, particularly in the rural area where the development of the optical infrastructure or expansion of the exiting telecommunication solutions are either too costly or unreachable. In order to successfully integrate the two technologies, there are some technical concerns in terms of Architectural aspects, Physical Layer features and Media Access Control (MAC) issues. This paper is mainly focused on the MAC-related issues, particularly the dynamic excess bandwidth allocations where the hybrid Passive Optical Network (hybrid PON) is employed as a back haul solution for the wireless counterpart. A mathematical model for a Genetic Algorithm (GA)-based dynamic excess bandwidth allocation algorithm is proposed in this paper. The algorithm is proposed and implemented in order to generate the optimum/near optimum solutions for the problem of excess bandwidth allocations over the converged scenario between hybrid PON and wireless technologies.**

Keywords—Genetic Algorithm; optical networks; wireless technology; optical and wireless technology integrations; excess bandwidth allocations;

I. INTRODUCTION

PON is the most promising candidate among optical access solutions in terms of maintainability and robustness. There have been various efforts on PON multiplexing techniques such as Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM) and Code Division Multiplexing (CDM). TDM-PON reduces the cost per subscriber and has inexpensive network components as it requires only one transmitter in the Optical Line Terminal (OLT), as well as only one type of transmitter in ONUs [1]. However, TDM-PON sacrifices the maximum available bandwidth per subscriber and limits the number of supported subscribers up to 32 [10]. On the other hand, WDM-PON provides multiple wavelength channels with a good security and protocol transparency which offers higher bandwidth and supports more subscribers [11]. In WDM-PON, a WDM transmitter, especially in a subscriber side is the most critical component where the associated transmitter should be precisely aligned with the allocated channel [10]. Unlike TDM-PON, in WDM-PON, the OLT needs to have an array of transmitters with one transmitter for each ONU. Each ONU also needs to have a wavelength-specific laser. Generally speaking, although PON has been viewed as an attractive solution for the "first/last mile" bandwidth bottleneck problem, extending fibre-based infrastructures of PON to the rural area is either too costly or inaccessible. Moreover, PON is unable to provide wireless access services. Worldwide Interoperability for Microwave Access (WiMAX, IEEE 802.16 [22]) standard comes into play as a wireless matching part for PON technology. WiMAX aims to reduce the equipment, operation and maintenance costs and capable of providing the low-cost, wide coverage, fixed and mobile broadband access connections with QoS provisioning scheme [22]. It also provides wireless access services for rural areas where the development of copper-base technologies or fibre-based broadband are too expensive or inaccessible. However, WiMAX copper-based back haul technology is still a controversial issue. This is the point where optical and wireless technology integrations come into play where PON can be used as a scalable, cost-aware and potential solution for WiMAX backhaul problem whereas WiMAX can extend PON infrastructure to the rural area with relatively lower cost. In order to successfully integrate the optical and wireless technologies, there are some challenging issues, which need to be addressed efficiently and effectively in order to provide the smooth End-To-End (ETE) technology integrations. The ETE MAC related issues such as ETE Quality of Service (QoS) provisioning schemes, upstream scheduling and ETE wavelength/bandwidth allocations are some of the challenging issues for the integrated scenario. Taking into account the wavelength routing and high-capacity of the WDM-PON, power-splitting and lower-cost of the TDM-PON as well as the high coverage and mobility features of the wireless counterpart, we are motivated to propose a dynamic excess bandwidth allocation algorithm for hybrid PON and wireless technology integrations by employing one of the most popular optimisation techniques, namely, Genetic Algorithm (GA). In the proposed algorithm, a GA solver is employed for the integrated scenario in order to find the optimum or near optimum solutions for the excess bandwidth allocation problems once per service cycle from all the available channels associated with a given SST to all the heavily loaded CSs which may be scattered over different places. A given GA solver provides efficient and effective techniques for optimisation and Machine Learning (ML) applications where genes and chromosomes (sequences of genes) are the basic instructions for building a given GA [12] and [8].

The remainder of this paper is prepared as follows. In Section II, the existing work related to the optical and wireless technology integrations along with a brief literature review of the optimisation techniques are discussed. The hierarchical wavelength/bandwidth allocations over the converged scenario are addressed in Sections III. The mathematical model for the proposed algorithm is detailed in Section IV followed by the implementations, conclusions/work in progress in Sections V and VI, respectively.

II. Related Work

The integrated scenario has been considered in three categories of: Architectural aspects, Physical Layer features and MAC Layer issues. As the work in this paper is related to the optimisation techniques for the MAC-related issues over the converged scenario, these two aspects are considered as follows. The MAC-related issues for the integrated scenario were discussed for the first time in [7] by raising several issues, e.g. bandwidth allocations, QoS support and user mobility. In [18], authors proposed a centralized scheduling algorithm which provides the better performance than the distributed scheme. However, no QoS mapping or up-link scheduling has been discussed. In [3], authors proposed a slotted-DBA algorithm which increased the bandwidth utilizations by reducing the signaling overhead. In [17], authors proposed a scheduling algorithm in which the QoS performance without bandwidth starvations for the lower-priority class of services was obtained. In [16], authors proposed a DBA algorithm which worked in three levels and showed improvements in QoS metrics for different classes of services. In [20], the authors of this paper investigated the possible challenging issues for integrated structure of the TDM-PON and WDM-PON and compared the six existing upstream scheduling mechanisms which showed the strong impact of using an efficient up-link scheduler over the converged scenario. Employing the traditional single channel, TDM-PON, which is mostly considered in literatures, where a group of ONUs share a channel and act as a back haul for the 802.16 BS, provides each BS with the capacity which is almost matched the 802.16 capacity [22]. However, the provided capacity does not seem to be enough when a given ONU is employed as a back haul solution for more than a single BS. This is the point where WDM-PON comes into play where multiple wavelengths are available over a same fibre channel. Thus, higher bandwidth can be provided, and more SSs can be supported. Providing multiple wavelengths over a single channel carries many challenging issues such as channel allocations, de-allocations and re-allocations.

Operational Research (OR) or optimisation is a group of mathematical modelling, statistical techniques and algorithms, which result in optimum/near optimum solutions for the complex problem [5], [9] and [13]. With the sole focus on telecommunication area, the optimisation techniques generally focus on improving just a couple of key metrics, e.g. CPU overhead, memory usage, power consumption, link utilisation, scalability, real-time support, etc. Linier Programming (LP), Dynamic Programming (DP) and Heuristic Methods such as Simulated Annealing (SA), Tabu Search (TS), Artificial Neural Network (ANN) and Genetic Algorithm (GA) [6], [15], [19] and [23], are some of the most popular optimisation techniques.

The authors in [14] proposed an algorithm based on LP and ANN in order to maximise the buffer memory and bandwidth utilisation in 3G networks. The authors in [15] applied GA techniques for spectrum assignments in cognitive radio networks. The authors in [21] utilized the GA techniques for the problem of antenna arrangements in mobile network and proposed a parallel GA model for multi-objective optimisation problem. The approach adopted in this paper differs from the above research by using the Genetic Algorithm (GA) techniques for the problem of optimum resource utilisations over the converged infrastructure for the next-generation broadband access networks. GA optimisation technique is a robust and reliable optimisation technique which requires little information to find the optimum/near optimum solutions (unlike LP optimisation techniques). It is also applicable for the no-stationary problems which change over time (unlike DP optimisation techniques) and can start working with no potential solution (unlike TS optimisation techniques). It can be programmed in order to do the specific task and does not have unpredictable operation (unlike ANN optimisation techniques). However, one of the GA's potential problems is identifying the population size which needs to be estimated correctly before running a given GA solver.

From all the above discussions, we are motivated to employ the GA optimisation technique, for the excess bandwidth allocations where the wavelength routing and high-capacity of WDM-PON, power-splitting and lower-cost of TDM-PON as well as the high coverage and mobility features of the wireless counterpart are combined. The major contribution of this paper is to provide a real-time and intelligent dynamic excess bandwidth allocation algorithm for the multi-channel PON integration with wireless technology for the next-generation broadband access networks. Before presenting the proposed algorithm, the next section first provides a view for the hierarchical wavelength and bandwidth allocation algorithm over the converged scenario.

III. Hierarchical Wavelengths and Bandwidth Allocations in Converged Architecture

This section briefly discusses how the wavelength/bandwidth is hierarchically allocated in this paper from the OLT in CO to the ONUs and then from a given ONU down to the associated BSs. In order to save space, the OLT/ONU is called as an SST, and the ONU/BS is called as a CS. A given SST is a component which is responsible for providing the resources for the associated CSs while a given CS is a component which asks for the resources from the related SST in a regular manner. A given SST can be a CS, and a given CS can be an SST at any time. In this paper, the OLT and SSs are the ultimate SST and CSs, respectively. However, the ONUs and BSs are the SSTs in terms of providing resources for the associated BSs and SSs, and CSs in terms of requesting resources from the OLT and ONUs, both respectively.

In this paper, the OLT with support of multi-channel is connected to the number of ONUs and is responsible for allocating wavelength/bandwidth to them whereas a given ONU with the same number of the channels is responsible for allocating the wavelength/bandwidth to the associated BSs. At the final stage, a given BS provides resources (wavelength/bandwidth) for the associated SSs.

The wavelength/bandwidth is allocated in three phases termed initialisation, intra-channel and inter-channel. The initialisation phase is only executed once during the network setup stage while the two other phases (phase two and phase three) are executed once per service cycle, Fig. 1.

During the initialisation phase, a given SST starts discovering the associated CSs by employing the MPCP Extension (MPCP Ext.) protocol [4] all over the converged scenario. The CSs then get registered, and a given channel ID will be granted to them. Based on the number of the CSs in the domain of a given SST, number of the available wavelengths on a given SST as well as the supported wavelengths on CSs, multiple CSs can share a single channel after the phase one execution is finished. The number of CSs sharing a single channel can be changed during the phase three after the traffic has been built up on each channel, which will be discussed later. The simplest way to run phase one is to divide the total number of the CSs by the total number of the available/supported wavelengths on a given SST which gives the average number of CSs per channel per SST. This allocation results in fair channel assignments at the beginning of the network setup stage. The output from this phase is multiple MPCP Ext. GATE messages, which carry the associated MAC addresses of the CSs and the allocated channel IDs.

During the phase two (intra-channel resource allocations phase), a given channel, which was allocated to the number of CSs through the initialisation phase, will be shared among related CSs in such an order that the allocated bandwidth will not be more than the actual need of a given CS. Therefore, if a given CS requested bandwidth less than the minimum guaranteed bandwidth, the requested bandwidth will be granted (lightly loaded CS) or else the minimum guaranteed bandwidth will be issued (heavily loaded CS). If there is any bandwidth left on a given channel after granting the minimum guaranteed bandwidth, it will be spent on the local heavily loaded CSs which are not satisfied with the minimum guaranteed bandwidth, or else it will be passed to the phase three (inter-channel phase resource allocations phase).

During the phase three (inter-channel resource allocations phase), a given SST receives the excess bandwidth from all the associated channels as well as the excess requested bandwidth from all the heavily loaded CSs and passes them to the GA solver. The GA solver is employed in phase three in order to find the optimum/near optimum solution for the excess bandwidth allocation problems from all the available channels among all the heavily loaded CSs. The GA output decisions aim to maximise the dynamic excess bandwidth utilisations in such an order that a given heavily loaded CS will not receive the excess bandwidth more than the actual need, and a given channel will not grant the excess bandwidth more than the available excess bandwidth.

As shown in Fig. 1, the GA solver runs as a part of phase three once per service cycle per SST and is fed with real-time parameters such as available excess bandwidth of each channel associated with a given SST as well as the excess requested bandwidth from each heavily loaded CS which may be scattered over the same or different channels of a given SST. These are the values which need be collected from a real/simulated network model and fed into the GA solver on a regular basis (e.g. once per service cycle).

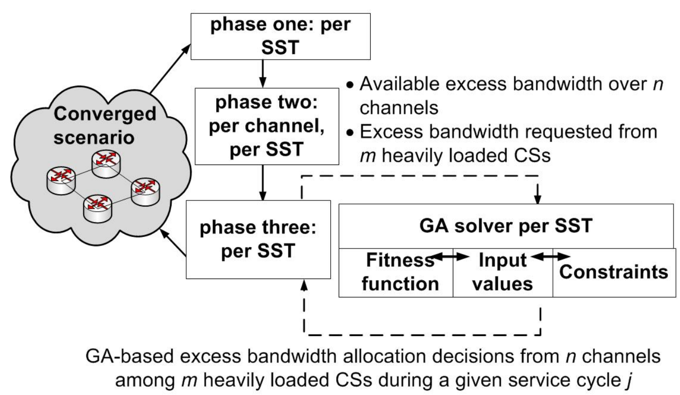

Figure. 1 The GA-based framework for dynamic excess bandwidth allocation algorithm

The next section discusses the mathematical model for the proposed GA-based dynamic excess bandwidth allocation algorithm.

IV. Mathematical Model

The mathematical model for GA-based dynamic excess bandwidth allocation algorithm for integrated hybrid PON with wireless technology is as follows.

Given:

1) W_i : Excess available bandwidth (bits) on a given channel i during a given service cycle k, where i = 1,…., n.

2) H_j : Excess bandwidth requested by a given heavily loaded source j during a given service cycle k, where j = 1,…., m.
3) $x_{i\,j}$: Excess bandwidth granted by a given channel i to a given heavily loaded source j during a given service cycle k, where i: i = 1,…., n and j: j = 1,…., m.
4) It is assumed that a given heavily loaded source j during a given service cycle k, where j = 1,…., m , can receive excess bandwidth from all the available channels.
5) It is assumed that a given channel i during a given service cycle k, where i = 1,…., n, can allocate the associated excess bandwidth to any heavily loaded sources.

Define:

1) The excess bandwidth will be allocated from a given channel i to a given heavily loaded source j during a given service cycle k not more than the actual need of a given heavily loaded source j, where i = 1,…., n and j = 1,…., m..

So: $$\sum_{i=1}^{n} x_{i\,j} \leq H_j \quad \text{for: } j = 1,\ldots, m \qquad (1)$$

2) The excess bandwidth will be allocated from a given channel i to a given heavily loaded source j during a given service cycle k not more than the available bandwidth (bits) of the channel i, where i = 1,…., n and j = 1,…., m..

So: $$\sum_{j=1}^{m} x_{i\,j} \leq W_i \quad \text{for: } i = 1,\ldots, n \qquad (2)$$

3) Excess available bandwidth (bits) on a given channel i during a given service cycle k (W_i), excess bandwidth requested by a given heavily loaded source j during a given service cycle k (H_j), and excess bandwidth granted by a given channel i to a given heavily loaded source j during a given service cycle k ($x_{i\,j}$), where i: i = 1,…., n and j: j = 1,…., m are all integer.

So: $$W_i \geq 0,\ H_j \geq 0,\ x_{i\,j} \geq 0 \qquad (3)$$

4) If W_i = 0, it means that there is no excess bandwidth available from given channel i during a given service cycle k, where i = 1,…., n.
5) If H_j = 0, it means that a given source j during a given service cycle k is not heavily loaded, where j = 1,…., m.
6) If $x_{i\,j}$ = 0, it means that no excess bandwidth is allocated from a given channel i to a given heavily loaded source j during a given service cycle k, where i = 1,…., n and j = 1,…., m.

Objective:

To maximise: $$\sum_{i=1}^{n} \sum_{j=1}^{m} x_{i\,j} \qquad (4)$$

The main objective for using GA solver is to maximise the total excess bandwidth allocated from all the channels to all the heavily loaded sources. The proposed GA algorithm tries to find the optimum/near optimum combinations of the allocated excess bandwidth from each channel to each heavily loaded source taking into account the available excess bandwidth (bits) per channel and the requested excess bandwidth per heavily loaded source. From the GA's point of view, the excess available bandwidth on a given channel i (W_i) and the excess bandwidth requested by a given heavily loaded source j (H_j) are the genes which are the input values for the GA solver. However, the excess bandwidth granted by a given channel i to a given heavily loaded source j ($x_{i\,j}$) is the chromosome which is the GA output decision values. Due to the dynamic nature of the Internet traffic the values for both genes and chromosomes can be changed during each service cycle. Therefore, the GA solver needs to be run once per service cycle as a function of different input values.

The next section discusses the mathematical implementation of the proposed GA-based dynamic excess bandwidth allocation algorithm for the converged scenario.

V. IMPLEMENTATIONS

MATLAB [2], which is a popular software for the numerical calculations and formulas with the vast library of functions and algorithms, was used for implementing and coding the requirements of the GA techniques such as the fitness function, the required constraints and chromosome encoding. The proposed GA-based dynamic excess bandwidth allocation algorithm for the converged scenario is implemented in this paper using MATLAB as follows.

[v, fval] = -ga (ObjectiveFunction, nvars, A, b, Aeq, beq, LB, UB, nonlcon, options) (5)

In this command, the GA function maximises with the default optimisation parameters replaced by values in the structure options, which can be created using the gaoptimset function, Table I.

In this paper, we employ the GA function and the associated objective function as follows in which we assume having eight excess bandwidth requests (x_1,…, x_8) from eight heavily loaded CSs and four excess available bandwidth (w_1,…,w_4) from four channels (donors).

[v, fval]= -ga (ObjectiveFunction, nvars, A, b, [], [], LB, [], [], options); (6)

ObjectiveFunction = @(v) ResourceAllocation (v, x_1, x_2 , x_3, x_4 , x_5 , x_6 , x_7 , x_8, w_1 , w_2 , w_3 ,w_4); (7)

Where:

1) -ga: It is the GA solver available in MATLAB library (to maximise).
2) ObjectiveFunction: It is the fitness function described in formula (4) in which the objective of using GA is to maximise the total allocated excess bandwidth from all the channels to all the heavily loaded sources.

TABLE I. PARAMETERS FOR THE GA FUNCTION IN MATLAB

[v, fval]	returns fval, the value of the fitness function at v
-	to maximise (+ to minimise)
ga	solver
ObjectiveFunction	Fitness function
nvars	Number of design variables
A	A matrix for linear inequality constraints
b	b vector for linear inequality constraints
Aeq	A matrix for linear equality constraints
beq	b vector for linear equality constraints
LB	Lower bound on x
UB	Upper bound on x
nonlcon	Nonlinear constraint function
rngstate	Optional field to reset the state of the random number generator
options	Options structure created using gaoptimset or the Optimization Tool

3) nvar: It is the total number of variables for the defined fitness function. As we assumed having eight heavily loaded CSs and four available channels (four donors) in a given servcie cycle, the total number of variables is 32 (eight multiple by four).
4) A: It is a matrix for linear inequality constraints. It was defined based on 1 and 2 formulas. For instance, in our example, the total allocated excess bandwidth to all the heavily loaded resources should not be more than the excess bandwidth on all channels. So, we can define these constraints as follows where $x_{i\,j}$ is excess allocated bandwidth from channel j to heavily loaded source i and W_i is excess available bandwidth (bits) on a given channel j:

$$\sum_{i=1}^{8} x_{i\,j} \leq \sum_{j=1}^{4} W_j \quad (8)$$

So, the following is the equal representation of the above formula:

$$x_{1\,1} + x_{1\,2} + x_{1\,3} + x_{1\,4} + x_{2\,1} + x_{2\,2} + x_{2\,3} + x_{2\,4} + \ldots + x_{8\,1} + x_{8\,2} + x_{8\,3} + x_{8\,4} \leq w_1 + w_2 + w_3 + w_4 \quad (9)$$

which can be encoded as follows: (this is the first row of the array A):

1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1; (10)

Moreover, the allocated bandwidth from all four channels to a given heavily loaded CS should not be more than what it has requested in the latest service cycle:

$$\sum_{j=1}^{4} x_{i\,j} \leq x_i \quad (11)$$

So, the following is the equal representation of the above formula for a given heavily loaded x_1 :

$$x_{1\,1} + x_{1\,2} + x_{1\,3} + x_{1\,4} \leq x_1 \quad (12)$$

which can be encoded as follows: (this is the second row of the array A):

1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 1, 0; (13)

And so on.

5) b: It is a vector for linear inequality constraints in which: A x ≤ b, therefore, it equals to:

   b=[w1+w2+w3+w4;x1;x2;x3;x4;x5;x6;x7;x8;w1;w2;w3; w4]; (14)

6) LB: It is the lower bound for the constraints. In MATLAB implementation, we consider this value as zero in order to provide only integer values (non-negative values) for the excess resource allocation. Therefore, by taking into account the total number of 32 variables in our example, the LB is defined as follows:
   LB = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]; (15)

7) opts: It defines the population size (GA iteration value) for the GA solver which is 100 in our implementation. We considered this value after capturing the extremely small improvements after the population size goes beyond 100.
8) $x_1, x_2, \ldots, x_8$: They are the excess bandwidth requested from eight heavily loaded resource. However, the model can be extended easily in order to support any number of heavily loaded resources. Moreover, $x_1, x_2, \ldots, x_8$ values need to be captured constantly once per service cycle and feed into the GA solver in order to provide the GA-based dynamic excess bandwidth allocation decisions based on the real-time traffic pattern.
9) w_1 , w_2 , w_3 ,w_4: They are the available excess bandwidth on four channels (four donors). However, the model can be extended easily in order to support any number of donors. Moreover, w_1 , w_2 , w_3 ,w_4 values need to be captured constantly once per service cycle and feed into the GA solver in order to provide the GA-based dynamic excess bandwidth allocation decisions based on the real-time traffic pattern.

In order to evaluate the outputs from the proposed GA algorithm, a given converged simulated scenario needs to be executed first for the different load values. The GA input values such as the excess available bandwidth per channel as well as the excess requested bandwidth per heavily loaded CS then need to be collected per load and per service cycle from the converged scenario on the second stage. The captured inputs from implemented scenario then need to be passed to the GA solver in MATLAB on the third stage. The GA decision outputs for the input parameters from simulated scenario then need to be captured and evaluated in fourth and fifth stages, both respectively, Fig. 2. We have selected OPNET Modeler [24], as a popular network simulation software, in order to generate input values for the GA solver implemented in MATLAB. This is our work in progress.

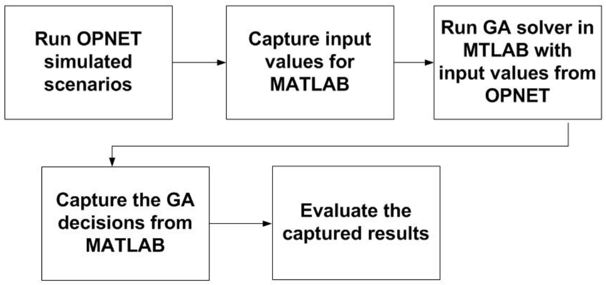

Figure. 2 Employing the GA solver for the input values from the OPNET converged scenarios

VI. CONCLUSION AND WORK IN PROGRESS

In this paper, a popular optimisation technique termed Genetic Algorithm (GA) was employed in order to propose the dynamic excess bandwidth allocation algorithm for the integrated scenario between hybrid PON and wireless technologies. The main goal of employing the GA technique was to maximize the dynamic excess bandwidth utilisations from the available channels associated with a given SST to all the related heavily loaded CSs which may be scattered over different channels with different excess bandwidth requests. The GA-based excess bandwidth allocation decisions are in such an order that a given heavily loaded CS will not receive excess bandwidth more than the actual need, and a given channel will not grant bandwidth more than the actual capacity. The work in progress for this paper is to employ the proposed GA-based dynamic excess bandwidth allocation algorithm in an on-line manner and in a given integrated scenario in order to evaluate the performance of the GA decision outputs on overall network performances.

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