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RESEARCH ARTICLE

QoS-aware ant-based route, wavelength and timeslot assignment algorithm for optical burst switched networks

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ABSTRACT

All-opticalnetworks are the aspiration of bandwidth-greedy applications providers and users such as telecom operators and scientific research centres. Because of the limitations of current network infrastructures, some optical switching paradigms have been proposed. Among these paradigms, optical burst switching (OBS) is seen as the most appropriate solution. However, OBS suffers from high burst loss ratio as a result of contention at the buffer-less core node. According to current optical technology reviews, cost effective optical memories are yet to be cost effective. In this paper, an ant-based route, wavelength and timeslot allocation algorithm is proposed to address high burst loss in OBS and improve the overall network performance. The solution was implemented in hierarchical time-sliced OBS and was evaluated through computer simulation where it was compared with shortest path (SP) algorithm. Simulation results show that the proposed algorithm outperforms SP in terms of burst loss ratio and delay. Copyright © 2015 John Wiley & Sons, Ltd.

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1. INTRODUCTION

To address bandwidth limitations of current electronic network infrastructures and to cope with the rapid growth of the Internet and bandwidth-greedy applications [1–7], optical wavelength division multiplexing (WDM) communication systems have been deployed in many telecommunications backbone networks. WDM is a multiplexing technology that enables various optical signals, known as wavelengths, to be transmitted by a single fibre. The principle of WDM is basically the same as frequency division multiplexing, in which several signals are transmitted using different carriers, occupying non-overlapping parts of a frequency spectrum. There are two wavelength bands at which optical fibres have very low signal loss; these two bands are 1300 and 1500 nm. Total available bandwidth for these two bands is estimated at 50 Tbps [8]. In the search for adequate solutions to cope with the growth of the number of Internet users and to satisfy large bandwidth requirements of current and future applications, three optical switching paradigms have been proposed: optical circuit switching [9], optical burst switching (OBS) [10, 11] and optical packet switching [12–14]. Another effort in this domain is optical code switching router that is intended to be utilised in hybrid WDM/optical code-division multiplexing networks [15].

Among the three common optical switching paradigms, OBS remains the promising paradigm and the most likely to be implemented in the near future to support growing number of Internet users and bandwidth-greedy applications [16–18]. However, OBS still suffers from high burst loss due to burst contention at the core nodes [19]. Burst contention occurs when two or more bursts contend for the same resource at the same time. In electronic communication networks, contention is solved via electronic memory used as buffers at the core network. In OBS, contention is solved using fibre delay lines (FDLs) [1], wavelength converters or deflection routing. All of these solutions are reactive in nature and thus do not provide optimum solutions to burst loss issue of OBS. Besides, some of these solutions, such as FDL and wavelength conversion, require hardware that is not yet available for commercialisation due to the immaturity of the technology [20–22]. Deflection routing does not require extra hardware, but it suffers from unpredictable and burst being delivered out of order. Besides the conventional OBS and its derivatives that perform switching in optical domain, many novel architectures have been proposed to improve OBS performance; these architectures are known as slotted or time variant OBS, and they perform switching in time domain as discussed in [23] and [16]. A review of time variant OBS can be found in [24]. One of the most important issues in slotted OBS is route, wavelength and timeslot assignment. Thus, in this paper, we propose and evaluate the performance of an adaptive and quality of service (QoS)-aware route, wavelength and timeslot assignment algorithm. The aim is to reduce burst loss ratio that is considered the primary metric of interest in any OBS network [18]. The algorithm also enhances delay, making it suitable for real-time applications. A comprehensive review of routing strategies in OBS is discussed in [25].

The proposed solution is developed based on AntNet algorithm [26], and it was implemented on hierarchical time-sliced optical burst switching (HiTSOBS) architecture [27] described in Section 3. AntNet was chosen for its adaptability and resilience. In the proposed AntNet algorithm, two types of ants were used: forward ants and backward ants. Forward ants are denoted as forward mobile agents and backward ants as backward mobile agents. The role of forward ants is to gather network information on their trip between a pair of source destination, while backward ants are used to update routing tables. One key difference between the proposed algorithm in this paper and similar work as in [19] is that the desirability factor of a path η depends on QoS requirements of the incoming bursts rather than the distance as is the case in most of the ant-based solutions. Two QoS attributes have been considered: maximum burst loss ratio and maximum delay denoted as D and L, respectively.

The rest of this paper is organised as follows: in Section 2, we review related works. Section 3 describes the architecture of HiTSOBS network. In Section 4, the proposed route, wavelength and timeslot assignment algorithm is elaborated. Simulation environment and parameters are discussed in Section 5. Simulation results are presented and analysed in Section 6. The paper is concluded in Section 7.

2. RELATED WORK

In this section, different route, wavelength and timeslot assignment (RWTA) schemes for slotted OBS are reviewed and analysed. In [28], the authors studied routing and wavelength and timeslot assignment problem for a circuit-switched time division multiplexed (TDM) wavelength-routed optical WDM network, so as to overcome the shortcomings of non-TDM-based route and wavelength assignment (RWA). The algorithm was applied on a network where each individual wavelength is partitioned in the time domain into fixed-length timeslots organised as a TDM frame. Moreover, multiple sessions are multiplexed on each wavelength by assigning a subset of the TDM slots to each session. In the paper, a set of RWTA algorithms was proposed and evaluated in terms of blocking probability. In those algorithms, shortest path routing algorithm was used for the routing part of the algorithm. Least load wavelength selection scheme was used for wavelength assignment, while a least loaded timeslot technique was proposed for timeslot assignment. The researchers claimed that their proposed RWTA algorithm performs better than random wavelength and timeslot assignment schemes. The disadvantage of the algorithm is the use of shortest path (SP) as routing algorithm, which is a static route selection algorithm making the proposed RWTA not suitable for dynamic traffic of OBS. The work carried out by the researchers in [29] is similar to that proposed in [28] and suffers for the same performance problems. In [30], Rajalakshmi and Jhunjhunwala also proposed an RWTA solution for wavelength-routed WDM networks to increase the channel utilisation when the carried traffic does not require the entire channel bandwidth. As in any TDM–WDM architecture, multiple sessions are multiplexed on each wavelength by assigning a subset of the TDM slots to each session. Different from the work in [28], the authors used fixed routing (FR) and alternate routing (AR) algorithms for route computation. First fit (FF) channel assignment algorithm was used for both wavelength and timeslot assignment.

The use of FR, AR and FF algorithms make the algorithm less complex and easy to implement, but the algorithm lacks scalability, and it is less adaptive as the paths are predetermined before bursts arrival. The work carried out by the researchers in [31] is similar to the one carried out in [30] and suffers from the same limitations. In [32], the researchers proposed a centralised control architecture and a timeslot assignment procedure for timeslotted optical burst switching (OBS) networks. In this centralised resource allocation technique, ingress nodes request timeslots necessary to transmit optical bursts, and a centralised control node that makes a reply according to the slot-competition result, route and wavelength are also assigned by the centralised node. The aim is to improve burst contention resolution and optical channel utilisation. Although the algorithm does achieve high resource utilisation, this is carried out at the cost of high buffering delay at the ingress node. Additionally, the centralised nature of the algorithm makes it non-scalable. Thus, it is not appropriate for large networks and expected implementation environment for OBS networks.

The researchers in [33] proposed and evaluated a distributed dynamic RWTA algorithm based on dynamic programming approach. Their goal was to minimise blocking probability. The proposed algorithm consists of three distinct parts; each part solves a sub-problem of the RWTA: routing part and wavelength assignment section and finally timeslot assignment section. The results were compared with SP algorithm and were reported to perform better than that algorithm. The drawback of this solution is the static nature of the routing and the possibility of high delay that was not tested in the paper. In [34], the authors proposed a hybrid of one-way and two-way signalling algorithm for slotted optical burst switching [35]. Through numerical analysis with comparison two-way signalling algorithm, the researchers argued that their hybrid signalling algorithm performs better than its competitor in terms of end-to-end delay.

The researchers in [36] proposed a new dynamic RWTA algorithm based on a principle known as the maximum contiguous principle. The proposed algorithm is called most-continuous-same-available resources. K shortest path routing algorithm was used to compute the routes in accordance with hops from small to large stored in the network nodes routing table. Although the simulation results suggest that the algorithm did reduce the blocking probability and achieved high resource utilisation, the algorithm has a high network overhead because it needs the real-time information such as network wavelength utilisation and timeslots allocation. Finally, in [37], the researchers proposed and evaluated the optical timeslot switching (OTS) technology, in which the fixed size timeslot is adopted as the basic switching granularity, and switching is done in the time domain, rather than wavelength domain. They also studied the route, wavelength and timeslot assignment (RWTA) problems. To this end, they introduced an adaptive weight function to the route and wavelength selection algorithm, and proposed several approaches for timeslot assignment such as the train approach, wagon approach and *p*-distribution approach. They have demonstrated that OTS and the underlying dynamic RWTA scheme perform better than conventional non-time-based OBS in terms of burst loss probability, QoS and class of service. The use of FDL is the only thing that can be reproached to this scheme. It is worth noting that this is the only paper, at the time of this writing, which has studied RWTA issue in the context of WDM OBS.

The researchers in [38] have proposed an ant-based routing algorithm to address the problem route and wavelength assignment in optical networks. The algorithm achieves better blocking probability during the routes establishment phase. The dynamicity and self-organisation of the ants are the main features of the algorithm. However, the algorithm works only for non-slotted OBS as it does not address the issues of timeslot assignment.

In [39], the authors discussed energy efficient translucent optical transport networks that show the importance of reduced energy in optical networks to support green optical network. Such considerations are out of the scope of this paper but are under investigation in ongoing research by the authors.

From the previous discussion, it can be observed that most of current RWTA algorithms use Open Shortest Path First and FF for route, wavelength and timeslot. AntNet has not been used to solve the problem. Moreover, solutions that use AntNet solve RWA problems; path desirability is dependent only on the distance travelled by the ants. To our best knowledge, this is the first paper that relates path desirability to QoS requirements. The proposed QoS-aware route, wavelength and timeslot assignment algorithm is described in Section 4. The results obtained from simulation demonstrate that the proposed algorithm has the potential to improve the performance of OBS networks.

3. THE ARCHITECTURE OF HIERARCHICAL TIME-SLICED OPTICAL BURST SWITCHING (HiTSOBS)

In this section, we describe frames structure and control plane operation of HiTSOBS. More details of the architecture can be read in [27].

(A) *Frame structure*

HiTSOBS was proposed to overcome the rigidity of frame size in previous slotted OBS, particularly in timeslotted OBS (TSOBS) [40]. Frame size (i.e. number of slots per frame) is a key parameter that has to be pre-configured at all switches of a slotted OBS. There are two opposing consequences related to frame size. On the one hand, a small frame size increases burst loss ratio as it increases contention probability; this is because overlapping bursts are more likely to pick the same slot number. On the other hand, a large frame size results in larger end-to-end delays, because each flow has access to a reduced fraction of the wavelength capacity (one slot per frame), leading to significant queueing delay at the ingress edge node. This loss-delay trade-off, dependent on frame size, is uniform across all traffic flows and cannot be dynamically adjusted to provide differentiated QoS in TSOBS. This makes TSOBS too rigid for practical use [27]. Frame rigidity problem was solved in HiTSOBS by designing a flexible hierarchical frame structure. HiTSOBS stems out from the hierarchical round-robin packet scheduler. Thus, HiTSOBS allows multiple frame sizes to concurrently coexist where slots lower in the hierarchy progressively offer lower rate service. Therefore, in HiTSOBS, delay-sensitive traffic classes operate at higher levels of the hierarchy, while loss-sensitive traffic runs at the lower levels concurrently.

For instance, let us assume that timeslots are numbered consecutively, starting from 0, and let us select radix r that defines the number of slots in each frame in the HiTSOBS hierarchy. Thus, the top-level (level 1) frame repeats every r slots. A burst transmitted at this level would occupy slots $l, l+r, l+2r, \ldots, l+(B-1)r$ where l is the timeslot at which burst transmission starts and B is the size of the burst in slot units. Assuming that we have radix $r = 10$ and the burst B_1 is of size 22 slots as shown in Figure 1 to occupy the third slot in the level 1 frame, this burst may be transmitted over timeslots $8043; 8053; 8063; \ldots; 8253$. Note that a given flow of bursts transmitted at level 1 has access to $\frac{1}{r}$ of the wavelength capacity.

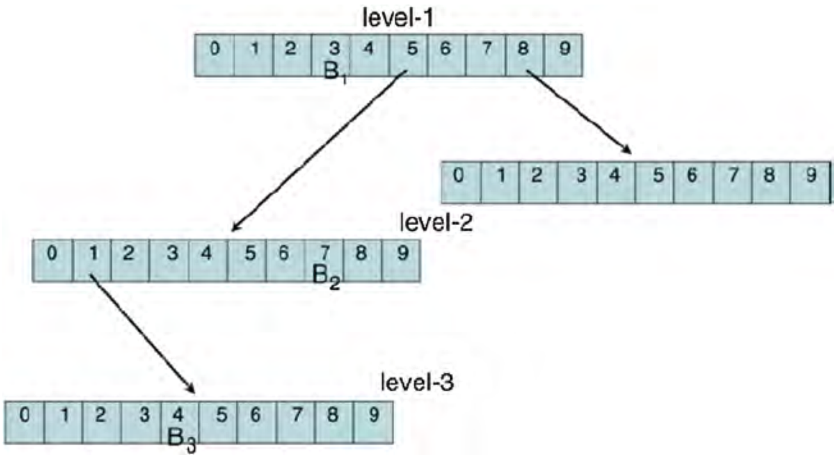

Figure 1. Frame structure of HiTSOBS [27].

It is worth mentioning that a slot in the level 1 frame may expand into an entire level 2 frame. For example, the fifth slot in the level 1 frame in Figure 1 expands into a level 2 frame. Successive slots in this level 2 frame are served in each successive turn of the fifth slot of the level 1 frame. The burst B_2, shown to occupy the seventh slot in this level 2 frame, may therefore be transmitted in timeslots $8175, 8275, 8375$ and so on. Note that a burst transmitted at level 2 therefore has access to $\frac{1}{r^2}$ of the wavelength capacity. Consequently, flows transmitting their bursts at level 2 of the hierarchy will have larger queueing delay at the edge compared with flows at level 1. However, the larger spacing between burst slices leaves more room for contention resolution using small optical buffers, making the losses for level 2 flows lower than for level 1 flows.

The previous structure can be extended to more levels. The rule is a slot in a level i frame transports the burst at $\frac{1}{r^i}$ of the wavelength capacity. Furthermore, one can easily map a timeslot number to its position in the frame hierarchy. The lth digit of the timeslot number read backwards denotes its position in the level k frame, and the process terminates when a leaf node is encountered.

(B) *Control plan operation*

To take into account QoS requirements, the ingress node of HiTSOBS accumulates data into bursts and classifies them into an appropriate QoS class. Like the traditional OBS network, HiTSOBS sends a burst header control packet prior to the arrival of a data burst. The control packet contains three pieces of information: the level in the hierarchy at which the burst will be transmitted, the start slot and the burst length. Upon receiving this information, a core node deduces the outgoing link for the bursts and then determines where the slot lies in its hierarchy corresponding to that output link. There are three possible outcomes:

(i) A frame does not exist at the requested level in the hierarchy: for simplicity, let Figure 1 as in [27] denotes the current hierarchy at the core node, and say the new burst is arriving at level 2 starting in slot 8234. The fourth slot in the level 1 frame does not have a level 2 frame under it, so there are two options: either create a new level 2 frame under this slot (if the slot is unoccupied) or use a delay line to delay the burst slices by one slot, moving it to the fifth slot in the level 1 frame, which already has a level 2 frame underneath, and in which the third slot may be used if available.

(ii) A frame exists at the requested level, but the required slot is unavailable: similarly, using Figure 1 as in [27] as an example, a new burst arriving at level 2 starting in slot 8375 collides with scheduled burst B_2. The new burst could be delayed using fibre loops by 10 slots to move it to the eighth slot in the same level 2 frame. Alternatively, the new burst could be delayed by three slots to move it to the other level 2 frame if it has its seventh slot available.

(iii) A frame exists, and the requested slot is available: in this case, the burst is assigned to the requested slot and passes through the switch in a cut-through manner without any delays.

The difference between control packet in HiTSOBS and that of traditional OBS is the addition of level information in the packet. However, there is a trade-off between single and multiple levels. Single level networks behave like traditional slotted OBS such as TSOBS and suffer from rigidity problem that is solved by multiple level frame structure. We did not study the optimal number of levels in a multi-level frame structure. However, because lower frames in the hierarchy have less bandwidth and suffer from higher delay, we believe that more than three levels will result in very high queuing delay, making the network not suitable for real-time applications.

4. QoS-AWARE AntNet ROUTE, WAVELENGTH AND TIMESLOT ASSIGNMENT ALGORITHM (Q-ARWTA)

Ant colony optimisation (ACO) has demonstrated better performance compared with other heuristic algorithms [41]. Different variants of ACO have been proposed for communication networks. The most commonly used ACO variant for solving routing issues in these networks is AntNet [26]. This algorithm was first used by Garlick and Barr [42] to address RWA issues in OBS. The researchers in [19, 43, 44] have used AntNet for various purposes to improve OBS performance. As of this writing, AntNet has not been used to address route, wavelength and timeslot assignment issue in OBS.

In the AntNet algorithm, there are two kind of ants: forward agents and backward agents. Forward agents are referred to as forward mobile agents (FMAs), and backward agents are known as backward mobile agents (BMAs). These two agents are used to determine a route between a source–destination pair. In this path finding process, backward ants utilise the useful information (path quality: distance, loss ratio and delay) gathered by the forward ants on their trip from source to destination. Based on this principle, no node routing updates are performed by forward ants. The purpose of the FMAs is to report network quality at a given time t to the backward ants. One important information is the delay that is reported in the form of trip time between each network node. The backward ants inherit this raw data and use it to update the routing table of the nodes. The basic operation of AntNet is explained as follows:

(i) At regular intervals and concurrently with the data traffic from each network node, mobile agents are asynchronously launched towards randomly selected destination nodes.
(ii) Agents act concurrently and independently and communicate in an indirect way through the information they read and write locally to the nodes.
(iii) Each agent or ant searches for a minimum cost path joining its source and destination nodes.
(iv) Each agent moves step by step towards its destination node. At each intermediate node, a greedy stochastic policy is applied to choose the next node to move to. The policy makes use of the local agent-generated and maintained information, local problem-dependent heuristic information and finally agent private information.
(v) While moving, the agents collect information about the time length, the congestion status and the node identifiers of the followed path.
(vi) Once they have arrived at the destination, the agents go back to their source nodes by moving along the same path as before but in the opposite direction.
(vii) During this backward travel, local models of the network status and the local routing table of each visited node are modified by the agents as a function of the path they followed and of its goodness.
(viii) Once they have returned to their source node, the agents die.

4.1. Route and wavelength assignment

From earlier sections, it is obvious that route and wavelength selection is an important issue in WDM networks. The solution for this problem needs to be robust and dynamic with minimum burst loss and low delay. Given the fact that AntNet has shown better performance compared with other heuristic algorithms in the literature, we have chosen to develop a QoS-aware RWA solution based on AntNet algorithm [26]. In this section, we describe the changes made to AntNet to reflect our approach. Although the work in [19] is similar to the scheme in this paper, we differ from that work in path selection criteria. Path selection is the most important part of the algorithm. Moreover, AntNet was chosen to take advantage of the cooperative and collaborative effort of ant colony to dynamically discover the best route between a source–destination pair in order to establish a light path. To do that, ants are periodically, every t, launched from each node with a given probability P to a randomly selected destination. Each ant is considered as a mobile agent. As such, it collects data on its trip as FMA performs routing table updating on visited nodes as BMA.

4.1.1. Pheromone deposit conditions and pheromone table.

In AntNet, pheromone concentrations are computed based on three sources of information:

- Congestion level: this is the measure of the number of contentions that has occurred through a specific output port. The greater the number of contentions, the smaller the pheromone deposition is on the path leading to that output port.
- Route distance: it is the length of the path from source to destination. Because shorter paths can decrease the congestion level among different flows, they are attributed to more pheromone making them more favourable. This means that pheromone intensity is inversely proportional to the length of a path.
- Desirability: this factor is problem dependent, and it gives heuristic information about the attractiveness of a path and it is represented by η.

In most of the ant-based routing and/or RWA algorithms, desirability is strictly related to the distance travelled by ants as in [19]. In this paper, the desirability is dependent on the QoS requirements of a burst. Thus, the path being considered for burst transmission must satisfy its QoS requirements before it is chosen. Two types of QoS requirements were imposed: maximum delay requirement D for real-time applications and maximum acceptable burst loss ratio L for non-real-time applications. To achieve this objective, two classes of burst were chosen: class 0 and class 1 for real-time and non-real-time applications, respectively. The two classes are denoted by $\mathbb{C} = \{0, 1\}$. The desirability factor $\eta : R^+ \to R^+$ is a function defined by Equation (1) and elaborated in Equation (2).

$$\eta_{hj} = \left(\frac{1}{f(y)}\right) \quad (1)$$

$$f(y) = \begin{cases} \mid D_{h,j}^{d+}(t) \mid & \text{If } \mathbb{C} = 1 \text{ (delay-sensitive bursts)} \\ \mid L_{h,j}^{d+}(t) \mid & \text{If } \mathbb{C} = 0 \text{ (loss-sensitive bursts)} \end{cases} \quad (2)$$

In Equations (1) and (2), variables h, j and d denote current node, current output port in consideration and the destination node, respectively. It should be noted that the desirability factor η that depends on $f(y)$ does not contain the distance parameter as is the case in [19]. This is a major difference between our work and that work.

Every network node has a pheromone table denoted by $\mathbb{T}$. Both updating and transition rules, described in the following sections, make use of this table. In $\mathbb{T}$, there exists a pheromone value for every output port, wavelength and timeslot.

4.1.2. Routing table update.

To vary and expand the search performed by subsequent ants and probabilistically favour good switching solutions, local updating (i.e. routing table update) rule is used to make efficient routing decisions. The local updating rule is only applied after a burst control packet has successfully reserved required resources and before forwarding the ant to the next node. Equation (3) is used to update the pheromone intensity at the output port where resource reservation has been programmed.

$$\tau_{ijw}(t+1) = \tau_{ijw}(t) + \beta_1 e^{-\varphi(\Delta D)|(\Delta L)} \quad (3)$$

In the previous equation, β_1 is also a user-dependent parameter, and it controls pheromone intensity when resource reservation is carried out successfully. Nevertheless, one should make sure that the pheromone value is not incremented too much to prevent the selection of local good solutions that may be globally bad solutions. The parameter φ determines how fast the pheromone should decrease.

4.2. Route selection

The selection of a path is determined based on the contents of the routing and pheromone tables. When a connection request arrives at source node, the next hop will be the neighbour node that has the highest selecting probability based on Equation (3). The visited nodes will not be selected. At that next hop, the same principle is applied and so on until the destination node.

In ant colony system, when an optimal path is found by ants, the pheromone deposit on that path continues to grow to the point that, even when the network state changes (a light-path set-up or its release), ants may not be able to quickly discover another optimal path for a new request. This is known as stagnation, and it is a determinant factor of the performance of the AntNet algorithm especially in WDM networks with wavelength continuity constraint as is the case in this study. Equation (4) is used to elevate this problem and obtain optimal solution.

$$n = \begin{cases} MaxProd\_j \in H_h^d(t)\{\tau_{ijw}(t)\eta_{hj}^{\alpha}(t)\} & \text{If } q \leqslant q0 \\ J & \text{If } q > q0 \end{cases} \quad (4)$$

In the previous equation, $q \sim N[0,1]$ and $q0$ is a user-specified parameter. τ_{ijw} is the pheromone concentration of a given output port where subscripts i, j and w denote input port, output port and wavelength, respectively; α is also another user-dependent parameter that controls the potential benefit of choosing an output link j with a desirability value of η_{hj}. H_h^d is the set of valid nodes to forward arriving bursts.

Depending on the value of α, the transition rule in Equation (4) creates a bias towards the nodes that are members of the paths with a large amount of pheromone. H_h^d is the set of valid nodes to forward the current burst, avoiding loops or ports without a feasible route to destination. $q0$ is the parameter used to balance between exploration and exploitation. On the one hand, if $q \leqslant q0$, the algorithm exploits favouring the best output port for the current request, and on the other hand, if $q > q0$, the algorithm chooses output port from the valid candidate list $H_h^d(t)$ based on the following probability function:

$$P_{inw}(t) = \left(\frac{\tau_{inw}(t)\eta_{hn}^{\alpha}(t)}{\sum_{h \in H_h^d} \tau_{ijw}(t)\eta_{hj}^{\alpha}(t)}\right) \quad (5)$$

In Equation (5), $H_h^d(t)$ represent the list of candidate nodes for path selection, and η_{hj}^{α} is the desirability function of the path to be selected between source and destination pair nodes h and d.

Route selection is dependent on QoS requirements (delay and loss) of arriving burst. This is similar to the work in [45] where delay was used as QoS constraint. Such considerations are not available in current RWTA algorithms.

4.3. Wavelength assignment

The route and wavelength assignment algorithm is run by the nodes for each new data transmission query. The objective is not only to calculate the best possible output port but also to choose the best wavelength. In the proposed algorithm, the wavelength allocation is based on the contents of pheromone tables, as in the FMAs. However, in this case, input port of the node itself is being considered.

$$\{n, \lambda\} = \{MaxProd\{\tau_{ijw}(t)\eta_{hj}^{\alpha}\} \mid j \in W_h^d(t), w \in W_h^d(t)\} \tag{6}$$

Based on Equation (6), the algorithm chooses λ and the output port n. The result of the route and wavelength allocation is the greatest value of the product of pheromone deposition τ_{ijw} of a certain output port and wavelength and the desirability (η_{hj}) of using such output port. To emphasise the use of the path that satisfies QoS requirements of the burst being transported, the value of α can be changed accordingly to favour the use of certain output ports.

The pseudocode of RWA scheme is shown in Algorithm 1.

4.4. Timeslot assignment

The priority-based segmented timeslot assignment (PSTA) algorithm developed by the authors in [46, 47] and shown in Algorithm 2 was used in this paper for timeslot assignment purpose. The frame hierarchy of the multi-core nodes HiTSOBS being studied is similar to those in [27], and Equation (7) is used to compute bandwidth allocation of a wavelength to a given timeslot in the hierarchy. However, timeslots occupation method differs. We have seen in Section 4 that, in HiTSOBS, a burst transmitted at a given level will occupy slots $l, l+r, l+2r, \ldots, l+(B-1)r$ where l represents the timeslot at which burst transmission starts, i is the order of the level in the hierarchy, B is the size of the burst being transmitted and r is the frame size in timeslots.

$$S_c = \left(\frac{1}{r^i}\right) C_w \tag{7}$$

where S_c is the bandwidth allocated to a given timeslot and C_w is the total bandwidth of a given wavelength. This equation was introduced for fair distribution of bandwidth between different timeslots at different levels.

In this paper, timeslots are occupied in a given level depending on the priority of the burst. The priority is directly related to QoS requirements as described in Algorithm 2. Thus, timeslots are reserved according to Equation (8). Algorithm 2 is designed based on the concepts of train and wagon described in [37]. Train approach is used for connection-oriented application, while wagon is used for non-connection-oriented applications. In train approach, the connection requests possibly reserve some timeslots periodically in the form of fixed position or certain number per frame. For instance, if a frame consists of N timeslots, one timeslot corresponds to $\frac{1}{N}$ bandwidth of

Algorithm 1 Q-ARWTA algorithm

$P^d(t) \leftarrow \emptyset$
Require $\mathbb{C}$
if $\mathbb{C} = 0$ **then**
  $P^d(t) = D^d(t)$
else if $\mathbb{C} = 1$ **then**
  $P^d(t) = L^d(t)$
end if
$AntCollide \leftarrow false$
if $P^d(t) = \emptyset$ **then**
  execute the algorithm using Equation (6)
end if
repeat
  if $\exists j \in H_h^d(t)$ **then**
    $q \leftarrow random()$
    if $q \leqslant q0$ **then**
      for all $j \in H_h^d(t)$ **do**
        Select output port $n \in H_h^d(t)$ based on Equation (4)
      end for
    else
      for all $j \in H_h^d(t)$ **do**
        Apply Equation (6) to compute observed probability distribution $F_J^d(j)$
      end for
      Select out port $n \leftarrow F_h^d(j)$
    end if
    $P^d(t) \leftarrow P^d(t) \cup \{link(h, n)\}$
    if resource reservation on $link(h, n)$ is false **then**
      $AntCollide \leftarrow true$
    end if
    if $AntCollide \leftarrow false$ **then**
      Run positive updating rule using Equation (3)
    end if
  else
    $AntCollide \leftarrow true$
  end if
until $FMAreachesdestination \parallel AntCollide \leftarrow false$
repeat
  $P^d(t) \leftarrow P^d(t) - \{link(h, n)\}$
  execute $\tau_{ijw}(t+1) = (1-\psi_1)\tau_{ijw}(t) + \psi_1\phi_{ij}\Delta\tau_{ijw}$ for global updating
until $P^d(t) = \emptyset \parallel BMAarrivessourcenode$

single wavelength. Therefore, in certain cases, the traffic flow may hold whole of wavelength. On the one hand, bigger switching granularity contributes to saving bandwidth resource and reducing the control complexity because the guard time between two timeslots will be saved. On the other hand, bigger switching granularity may lead to higher burst loss ratio as such bursts are easier blocked than those with smaller granularities. Thus, one should be careful in designing switching granularity because once the switching granularity is formed at ingress node, it will not be separated to individual timeslots at intermediate core

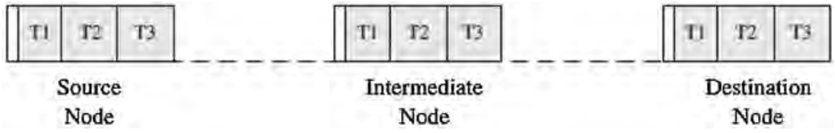

Figure 2. Illustration of train approach [37].

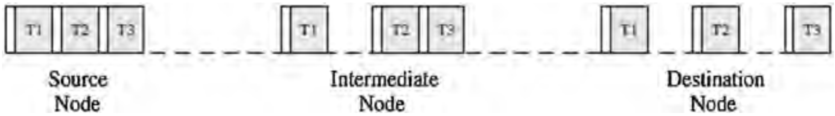

Figure 3. Illustration of wagon approach [37].

nodes even if it includes multiple timeslots as depicted in Figure 2.

For non-connection-oriented traffic, the traffic can occupy the timeslot as successively as possible at ingress node, but a guard time must be inserted between any two adjacent timeslots; therefore, the timeslots can be split at intermediate node as shown in Figure 3.

In this case, new control packet should be generated at that intermediate to notify the changes in the burst information. The disadvantage of the wagon approach is that a little bandwidth is sacrificed. But this sacrifice is worth as it helps in improving the timeslot scheduling flexibility so as to significantly reduce the blocking probability, particularly at high traffic load. Furthermore, the wagon scheme can also hold relatively integrated switched granularity at low traffic.

$$S_R = i + (B - \left\lceil \frac{(B-1)}{z} \right\rceil (z-1)z) + \left\lceil \frac{(B-1)}{z} \right\rceil r \quad (8)$$

In Equation (8), B denotes burst size, z represents the size of the train (number of coaches), i is the initial position of timeslot reservation and r is the frame size in timeslots as in Equation (8). The pseudocode of PSTA is described in Algorithm 2.

The list of symbols used in the previous equations and in the algorithms are described in Table I.

The complexity of the proposed algorithm is based on the network model represented by $G = (V, E, W, T)$ where V represents the set of vertices (nodes) and E represents the set of edges (links), each one with W wavelengths and each of which has T timeslots. Because the running time or the complexity of graph algorithms is estimated in terms of the number of vertices of the graph that is input, the worst case time complexity of the algorithm added by an ant throughout its travelling period will be $O(VWT + 2V^2) \sim (V^2)$, assuming that $V \sim W$. This computational complexity is calculated based on the time consumed in the lookup process of the best wavelength, timeslot and output port to transmit a particular burst that adds a cost of $O(VWT)$. After the assignment of the wavelength and the timeslot, the complexity added at every hop of the ant path discovery is reduced to $O(V)$ as the transition and updating rules involve an operation that can be run in constant time

Algorithm 2 PSTA algorithm

Notations:
t_a: Arrival time of a burst. b_c : Class of the Burst. b_{qreq}: Burst QoS requirements. b: Burst to be transmitted. z: Number of coaches in a train. D: Maximum delay requirement. L: Maximum loss requirement. T_n^m: Timeslots to transport burst between next node m and the current node n.
for all b **do**
  initialise candidate timeslots
  $T_n^m \leftarrow t$
  if $b_c \leftarrow 0$ **then**
    $b_{qreq} \leftarrow b$
    Execute High_PSTA(z)
  else if $b_c \leftarrow 1$ **then**
    $b_{req} \leftarrow D$
    Execute low_PSTA(z)
  end if
end for

($O(1)$); however, this must be applied at every possible node of the candidates list and at the most can be in the order of $O(V)$. Thus, the forward and backward processing of the ant in the proposed algorithm adds a complexity of $O(2V^2)$. We observe that time complexity of the proposed algorithm is similar to that of Ant Colony Route and Wavelength Assignment Algorithm (ACRWA) [19] with improved burst loss ratio and delay.

5. NETWORK MODEL, SIMULATION ENVIRONMENT AND PARAMETERS

The simulation model adopted for evaluating the developed algorithm is similar to the one in [47], which is a mesh WDM OBS network defined by $G(V, E, W, T)$. In this model, $V = \{v_1, v_2, v_3, \ldots, v_{|V|}\}$ represents the core nodes in the network, and $E = \{e_1, e_2, e_3, \ldots, e_{|E|}\}$ is for the collection of bidirectional links that interconnect different core nodes. $W = \{w_1, w_2, w_3, \ldots, w_{|W|}\}$ represents the number of wavelength per link, and finally, $T = \{t_1, t_2, t_3, \ldots, t_{|T|}\}$ defines the number of timeslots of each wavelength; in other words, it defines the frame size. $|V|$,

Table I. List of symbols.

Symbols	Description
$\mathbb{C}$	A set that defines number of classes used in the algorithm
$\mathbb{P}$	Set of paths found by the ants
D	Maximum delay parameter for delay-sensitive applications
L	Maximum loss parameter for loss-sensitive applications
λ	Wavelength
α	Weighted factor to favour desirability over pheromone intensity
β_1	Control pheromone intensity in case of positive reservation of resources
η	Desirability of a path
τ	Pheromone intensity
φ	Decay parameter to control pheromone deposit on a path
ρ	Traffic load
q^0	Control path exploration (discovery) by ants
P	Probability function for choosing output to transmit a burst to its destination
W	Set of candidate wavelength for selection
H	Set of candidate nodes for selection
B	Average burst size

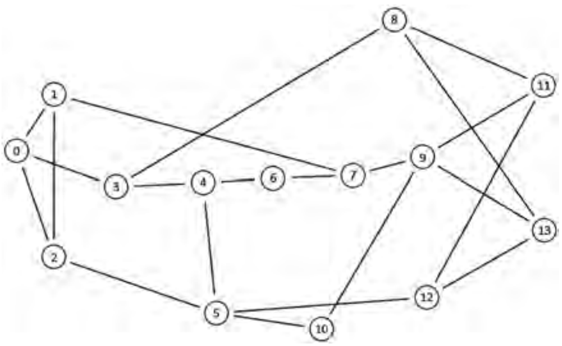

Figure 4. Simulation topology, NSFNET.

$|E|$, $|W|$ and $|T|$, respectively, stand for total number of core nodes, total number of fibre link, total number of wavelength and the frame size. Each link has the same number of wavelength and capacity, 8 and 10 Gbps, respectively. Two cases of timeslot sizes were investigated: 1 and 4 μs. Wavelength converters were not used in this study because of their immaturity and high cost.

In this paper, we assume that each link consists of a pair of an opposite one-way fibre. Wavelength continuity constraint is applied. So, any connection establishment request from the source node to destination node through different links will use the same wavelength. However, a connection may be assigned different timeslots between source and destination. Additionally, a flexible and hierarchical frame structure is assumed as in HiTSOBS architecture where different frame sizes can coexist in the network to support QoS. The frame structure of an HiTSOBS network is depicted in Figure 1. As in [27], frame size is chosen to be 10 timeslots. However, timeslot occupation differs as described earlier in Section 3. Timeslot assignment procedures are described in Section 4.4. All the simulations were run using NSFNET, the American National Science Foundation Network, topology as depicted in Figure 4. Burst loss ratio is expected to be very low, and thus, bursts retransmission is not considered. For simplicity, the source and destination pairs are uniformly distributed among all flow requests.

Table II. General simulation parameters.

General parameters	Values
Wavelengths per fibre link	8
Wavelength capacity (Gbps)	10
Frame size (timeslot)	10
Burst Size (KB)	125
Timeslot size (μs)	1 and 4
Number of levels per frame	2
Traffic model	*Poisson*
Number of flows	8000
Number of simulation runs	30

Table III. Quality of service (QoS) parameters [6, 48–51].

QoS requirements	Class 0	Class 1
Max delay (ms)	100	400
Max loss ratio	$\leqslant 10^{-3}$	$\leqslant 10^{-3}$
Min bandwidth (Mbps)	$\geqslant 1243$	$\geqslant 1000$
Percentage of traffic	60 per cent	40 per cent

Table IV. AntNet simulation parameters.

Factors	Description	Levels
ψ_1	Control pheromone evaporation	0.001
β_1	Control pheromone intensity in case of positive reservation of resources	0.001
φ	Decay parameter to control pheromone deposit on a path	0.75
$q0$	Control path exploration (discovery) by ants	0.9
α	Weighted factor to favour desirability over pheromone intensity	2.0

Tables II, III and IV list the simulation parameters used to evaluate the developed ARWTA algorithm.

The values chosen in Table IV are based on the experiments in [19]. Any change in the parameters will result in different results as discussed in [19]. Two classes of bursts have been considered in this study: class 0 and class 1. Class 0 bursts have the highest priority, and they represent 60 per cent of the entire traffic. Class 1 bursts represent low priority data, and they make up 40 per cent of the entire traffic. Examples of class 0 and class 1 data are high video conference and telemedicine data, and emails, FTP and telnet, respectively [6, 48].

6. RESULTS DISCUSSION AND ANALYSIS

In slotted OBS, timeslot size is an important parameter as it determines the switching speed of the architecture. The evaluation was carried out using two different timeslots : 1 and 4 µs. Figures 5 and 6 show loss results for both cases, respectively.

The results depicted in Figures 5 and 6 demonstrate that smaller timeslots perform better than larger timeslots in terms of burst loss ratio. The reason for this can be traced back to OBS paradigm where larger burst sizes are easier to be blocked than the smaller-size burst, especially at heavy traffic load. Thus, with smaller switching timeslot, the bursts get processed faster. This minimises the possibility of being dropped. Additionally, the proposed ant-based RWTA scheme outperforms SP algorithm. The superiority of our algorithm over SP can be explained by the fact that ants collaborate coherently to find the best path to route the burst based on its specific requirements and these paths are saved in some dedicated queues at the edge nodes for the next use if they remain the best.

The results shown in Figures 7 and 8 depict the findings of the simulation for delay comparison. The evaluation was carried out using two different timeslots values: 1 and 4 µs.

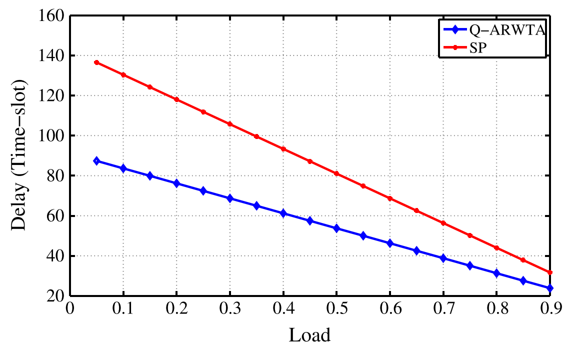

Figure 7. Delay results of 1 µs.

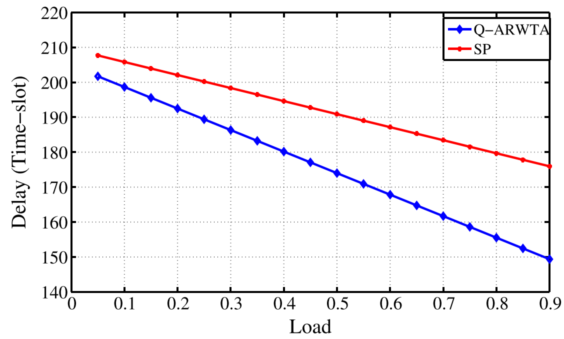

Figure 8. Delay results of 4 µs.

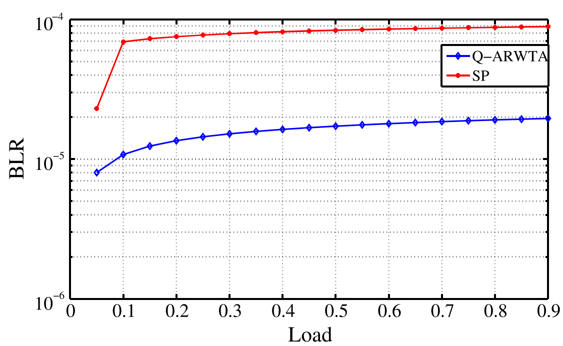

Figure 5. Burst loss ratio results of 1 µs.

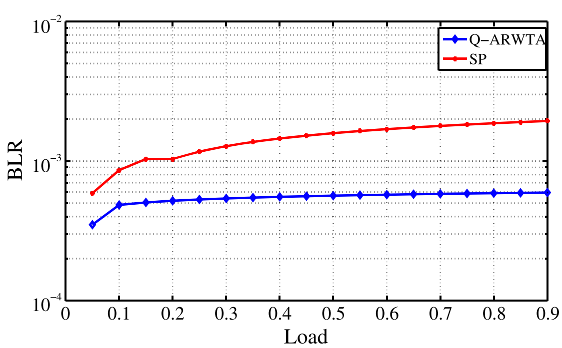

Figure 6. Burst loss ratio results of 4 µs.

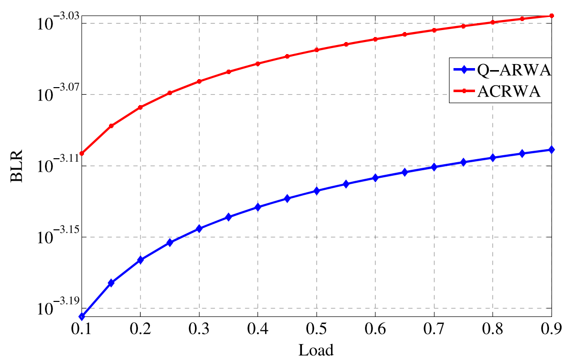

Figure 9. Loss results RWA-QoS and ACRWA.

On the one hand, the results shown in Figures 7 and 8 prove that smaller timeslots produce better results compared with larger timeslots in terms of delay; this implies that the thinner the switching granularity is in a slotted OBS, the lower the delay and thus more suitable for real-time applications.

Additionally, we have carried out an investigation in which the proposed QoS-aware RWA algorithm was compared with the one proposed in [19]. Simulation results are shown in Figure 9. The obtained results demonstrate that choosing paths based on QoS has improved network performance in terms of burst loss ratio. This is attributed to the fact that ants, in search for route, take into consideration bursts-specific requirements. The proposed algorithm addresses route, wavelength and timeslot assignment. However, in comparison with ACRWA [19], only the RWA part was compared with ACRWA because ACRWA does not address timeslot assignment. Simulation parameters are similar to those in Tables III and IV.

7. CONCLUSION

In this paper, we have developed and analysed QoS-aware ant-based route, wavelength and timeslot assignment algorithm for OBS networks. The algorithm was implemented in HiTSOBS network and was evaluated via computer simulation and compared with SP algorithm. Simulation results demonstrate that the developed scheme outperforms SP algorithm in terms of burst loss ratio and delay, making it more suitable for real-time applications. The use of QoS as the desirability criteria and the implementation of PSTA algorithm contribute to high performance of the algorithm. Currently, research is being undertaken for more performance investigations. Future works include extending QoS attributes and energy consumption consideration for a green OBS development. Furthermore, fault tolerance is another area of investigation.

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