Journal of Applied Sciences

ISSN 1812-5654

science alert

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 7 (23): 3796-3800, 2007
ISSN 1812-5654
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Four Wave Mixing Aware Wavelength Assignment Using Ant-Based Algorithm

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Abstract: An Ant-based algorithm is proposed for Four Wave Mixing (FWM)-Aware Wavelength Assignment with the objective to optimize light path connection according to the wavelength clash and wavelength continuity constraints while guaranteeing acceptable signal quality according to FWM crosstalk. Performance results show that the proposed ant-based algorithm outperforms the Assign Shortest Path First (ASPF) algorithm. It is found that in the case of Ant algorithm, the induced blocking probability is lower compared to ASPF algorithm in the presence of FWM.

Key words: Ant-based algorithm, four wave mixing, routing and wavelength assignment, bit error rate, non linear impairments, Q-factor

INTRODUCTION

In a wavelength routed network, the signal quality is subject to a variety of impairments introduced by the transmission line or switching equipment (Ramamurthy *et al*., 1999). In addition to advanced modulation formats and other similar techniques to overcome or reduce the impact of signal impairments, the network designer may also use appropriate Routing and Wavelength Assignment (RWA) algorithms that consider the effect of the signal impairments. Generally, impairments can be classified into two categories, linear and nonlinear. For non-linearity impairment, it is significantly more complex as they generate not only dispersion on each channel, but also crosstalk between channels. These fiber nonlinearities include Four-Wave Mixing (FWM), Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Stimulated Raman Scattering (SRS). In this study, we demonstrate an-based wavelength assignment algorithm for transparent optical networks based on the physical layer nonlinear impairment, FWM crosstalk. Some nonlinear impairments that have been studied are: SPM (Cerutti *et al*., 2002) and FWM (Fonseca *et al*., 2003, 2004, 2005). Ant Colony Optimization (ACO) has been applied in the linear impairment problem in ASE constraint-routing (Tan *et al*., 2007) and there are also quite a number of approaches proposed (Fonseca *et al*., 2003, 2004) for FWM-aware wavelength assignment. Most of the FWM-aware RWA approaches such as in (Fonseca *et al*., 2003, 2004) optical network are mainly analysis based on the effect of frequency grid, wavelength set position and connection length. None of them addresses the issue of correlation of input light power, optical channel and FWM crosstalk power and none of them is using the Ant-based algorithm for FWM-aware wavelength assignment problem. The premises of the proposed ant-based algorithm are that it gives lower FWM crosstalk to ensure signal quality requirement and allows high optical channel to fulfill the wavelength continuity and wavelength clash restrictions at the same time.

ACO (Ant Colony Optimization) has been applied in many domains such as traveling salesman (Dorigo and Gambardella, 1997a), networking routing (Sim and Sun, 2003), graph colouring (Costa and Hertz, 1997), quadratic assignment (Gambardella *et al*., 1999), machine scheduling (Bauer *et al*., 1999), vehicle routing (Bullnheimer *et al*., 1999) and frequency assignment (Maniezzo and Carbonaro, 2000). Ant System (AS) was the first ACO algorithm to be proposed in literature (Dorigo *et al*., 1996). Its main characteristic is that the pheromone values are updated by all the ants that have completed the tour. MAX-Min Ant System (MMAS) (Stutzle and Hoos, 2000) is an improvement over the original Ant System idea. MMAS introduces two changes: only the best ant can update the pheromone trails and the minimum and maximum values of the pheromone are limited. Another improvement over the original Ant system was Ant Colony System (ACS) introduced by Dorigo and Gambardella (1997a, b). The most interesting contribution

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of ACS is the introduction of a local pheromone update in addition to the pheromone update performed at the end of the construction process where the update is performed by all the ants after each construction step.

IMPLICATION OF FWM IN Q-FACTOR AND BER

In WDM system with C frequency channels, at any particular channel frequency, there will be a number of FWM waves generated from various combinations of interacting signals whose frequencies satisfy:

$$f_{FWM} = f_i + f_j - f_k$$

Where f_i, f_j and f_k are the signal light frequencies and f_{FWM} is the four-wave mixing light wave frequency. The time-average optical power generated at frequency f_{FWM} is given by (Inoue *et al.*, 1994):

$$P_{FWM}(f_i, f_j, f_k) = \eta\left(\frac{1024\pi^6}{n^4\lambda^2c^2}\right)\left(\frac{L_{eff}}{A_{eff}}\right)^2 (d\chi)^2 P_iP_jP_ke^{-\alpha L} \quad (1)$$

Where:

- η = Four-wave mixing frequency
- n = Fiber refractive index
- λ = Wavelength
- c = Speed of light
- L_{eff} = Effective length of the fiber ($L_{eff} = (1-e^{-\alpha L}/\alpha)$)
- A_{eff} = Effective mode area of the fiber
- d = Degeneracy factor ($d = 3$ for $i = j$, $d = 6$ for $i \neq j$)
- χ = Third-order nonlinear susceptibility
- P_i = Input power of the frequency f_i
- α = Fiber loss coefficient
- L = Fiber length

Total power generated at frequency f_m may be expressed as a summation (Inoue *et al.*, 1994):

$$P_{tot}(f_m) = \sum_{f_k = f_i + f_j - f_m} \sum_{f_j} \sum_{f_i} P_{FWM}(f_i, f_j, f_k) \quad (2)$$

The FWM interference noise power can be expressed as (Inoue *et al.*, 1994):

$$N_{FWM} = 2b^2P_s\frac{P_{FWM}}{8} \quad (3)$$

Where:

- b = The quantum efficiency
- P_s = The signal light power at the receiver which can be expressed as $P_s = P_0e^{-\alpha L}$, with P_0 represents the input light power to the fiber

The signal to noise ratio (SNR) can be expressed as factor Q (Inoue *et al.*, 1994) where N_{th} and N_{sh} are the thermal and shot noise, respectively, which are very small and could be neglected in front of N_{FWM}:

$$Q = \frac{bP_s}{\sqrt{N_{FWM}}} = \frac{2\sqrt{P_0e^{-\alpha L}}}{\sqrt{P_{FWM}}} \quad (4)$$

In the Gaussian noise approximation, the Bit Error Rate (BER) for On-Off keying signal with intensity modulation can be calculated through:

$$BER = \frac{1}{\sqrt{2\pi}}\int_Q^{\infty} e^{-\frac{-t^2}{2}}dt \quad (5)$$

All the connections that are accepted in the network should obey the network layer criterion with the wavelength continuity restriction (free-resources status) and the physical layer criterion that is the quality of the optical signal with BER = 10^{-9}. The total crosstalk power at the destination for the connection is found by adding the contributions of each link as follows:

$$P_{dest} = \sum_{c=1}^{H} P_{tot}(f_m) \quad (6)$$

Where, H is the number of hops of the route i, j ≠ k, 1, 2, ...,C. C is the number of active channels in each connection. With the total crosstalk power at the destination, the FWM interference noise power and the Q factor of the request are obtained by using Eq. 3 and 4. After that, the decision about the blocking or not the connection is made.

ANT-BASED ALGORITHM FOR FWM-AWARE WAVELENGTH ASSIGNMENT

In ACO algorithm, each ant generates a complete tour by choosing the next node according to a probabilistic state transition rule and is given by:

$$P_{ij}(n) = \begin{cases} \dfrac{\tau_{ij}^{\alpha}(t)\eta_{ij}}{\sum \tau_{is}^{\alpha}(t)\eta_{is}} & ,j,s \notin tabu_n, j,s \in adj_i \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

Where, P_{ij} denotes the probability with which the ant in node i choose to move to next node j. We defined, $\tau_{i,j}(t)$ as the trace intensity (pheromone in the case of real ants) on the path ij at time t and η_{ij} is the inverse of the length of path ij (in our case it is the inverse of the span length from node i to node j) and the span length is the shortest path for all pair source to destination ij. The objective of using shortest path as heuristic information at the beginning is to optimize the light path connection according to the wavelength clash constraint. For each source-destination ij, there is a list of links for each route and is represent by link(l) where l is the number of link in the network. Besides, $tabu_n$ (n = 1,2,…,m) is a list of reporting nodes which ant n has visited (the link in the route ij that has been assigned wavelength nth for wavelength clash constraint) and nth ant equals to the number of wavelength used in wavelength assignment. In our case, adj_i is a list of node that has not been assigned by any wavelength. Pheromone trail are updated after all the ants have constructed their solutions as follows:

$$\tau_{ij}(t+n) = \rho.\tau_{ij}(t) + \Delta\tau_{ij} \quad (8)$$

Where:

ρ = A coefficient that represents the trace's persistence

$(1-\rho)$ = The evaporation

$$\Delta\tau_{ij} = \sum_{n=1}^{m}\Delta\tau_{ij}(n) \quad (9)$$

$$\Delta link(a) = \begin{cases} Q_0 & \text{if the nth ant use link(a) in its tour.} \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

$$\Delta\tau_{ij}(n) = \begin{cases} Q_0 & \text{if the nth ant use link(a) in its tour(i, j)} \\ & \text{and } \Delta link(a) \le Y \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

Where:

$0<p<1$ = A coefficient which represents the residual pheromone of trail in the process when the ants search their closed tours

Q_0 = A constant

$\Delta link$ (a) = The usage of each link after all the ants have performed the wavelength assignment

Equation 10 is to ensure that the intersection of wavelength that causes FWM crosstalk is acceptable in each link(a) for all the ants after wavelength assignment. Thus, this results in lower blocking. Y is a design parameter that allows the number of wavelength intersection for each link in the network. As Y approaches (0.01*C), the optimization problem becomes maximization of light path connection and as Y approaches zero this guarantees the quality signal that is free of FWM crosstalk. Thus, the proposed algorithm allows the optimization that maximizes the light path connection according to wavelength clash restriction while guaranteeing acceptable FWM crosstalk for each signal. The proposed Ant-based algorithm is as follows.

- Initialize the trace matrix.
- Put k ants on.
  For n = 1 to k
  Repeat for each wavelength k = 1, 2,…, C
    Repeat for each route (i-j)
    Choose, with probability given by Eq. 7, the unassigned nodes (adj_i) as the next hop from those not yet chosen
    Put the chosen node in the tabu list of the n^{th} ant
    (this cycle is repeated by N*N times)
  (this cycle is repeated by C times)
  End for
- For n = 1:k
    Carry the solution and compute Δlink(a) for a = 1:l. l is the number of link in the network.
    Update the best assignment found. (Total assignments that contribute reasonable FWM crosstalk)
  End for
- For each coupling (i,j), calculate $\Delta\tau_{ij}$ according to Eq. 9
  Update the trace matrix according to Eq. 8.
  End for
- If not (End_Test)
    Empty the tabu lists of all the ants.
    Goto 2
  Else
    Print the best assignment and Stop.
  End

The Ant-based algorithm used in our case is the Ant System (AS) (Dorigo *et al*., 1996). Its main characteristic is that the pheromone values are updated by all the ants that have completed the tour. In this design, the number of ants is equal to the number of optical channels.

RESULTS AND DISCUSSION

The results of the proposed ant-based algorithm as compared with the one using Assign Shortest Path First (ASPF) algorithm is tested on the topology as described in Fig. 1. ASPF algorithm allows the optimization of light path connection according to wavelength clash and wavelength continuity constraints but ignores the signal

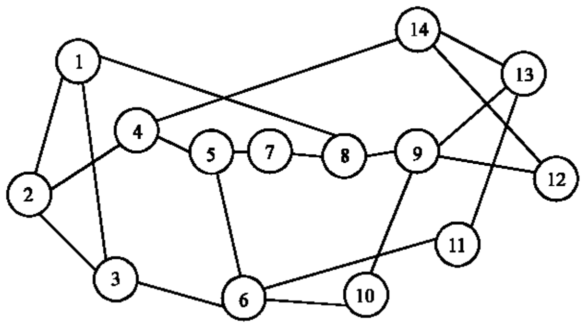

Fig. 1: NSF networks

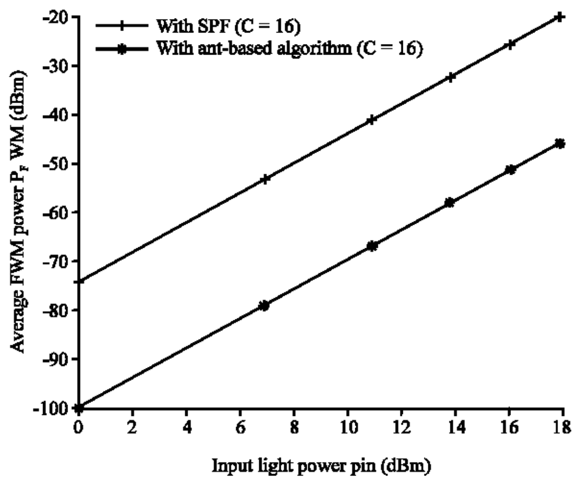

Fig. 2: FWM power versus Input light power for C = 16

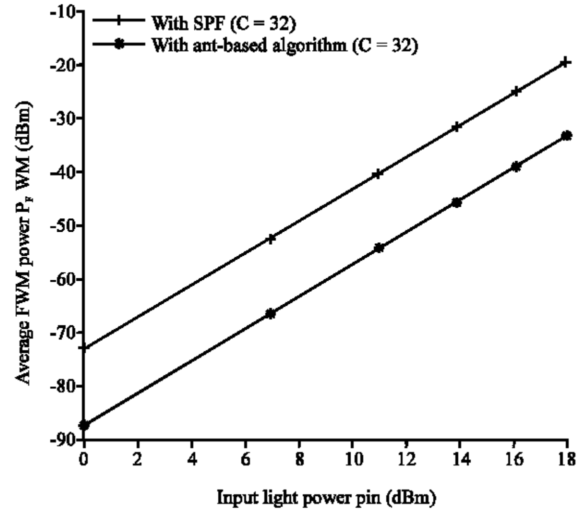

Fig. 3: FWM power versus Input light power for C = 32

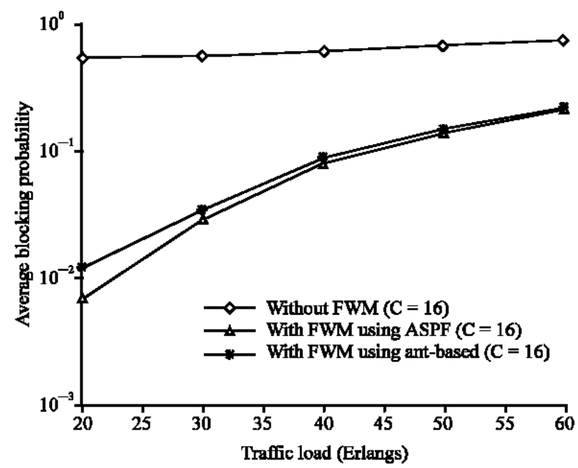

Fig. 4: Blocking probability versus traffic load for C = 16

quality requirement. The ACO parameters; $Q_0 = 0.01$, $\alpha = 1$ and $\rho = 0.5$, $Y = 0.01*(C/2)$ are used in the experiments. The number of ants k is equal to the number of optical channels (C = 16 and C = 32) and the number of iterations is equal to two. The maximum hop length is restricted to 5 for this topology in the shortest path algorithm for comparison and all requests arrive from nodes to nodes following the shortest route (minimum hop routing).

Figure 2 and 3 show the average FWM power versus input light power P_{in} using Ant-based algorithm and ASPF algorithm(Assign the Shortest Path First) for optical channels of 16 and 32 for comparison in NSF network. As expected, the performance of the proposed Ant-based algorithm is always much better than those using ASPF algorithm when FWM crosstalk is taken into consideration. For the same value of P_{in}, the proposed ant-based algorithm indulges less FWM crosstalk in both optical channels compared to ASPF wavelength assignment algorithm. The difference between the algorithm results is that the good performance of the proposed ant-based algorithm is more apparent in low optical channels (C = 16). This is because lower optical channel, there is less intersection wavelength at each link. It is clear from the results that FWM is one of the serious factors limiting system performance in higher optical channels.

The blocking probability as shown in Fig. 4 and 5 for both optical channels (C = 16 and C = 32) using Ant-based algorithm is always higher than those without FWM crosstalk noise (ideal case). However, the proposed ant-based algorithm still outperforms the ASPF algorithm in the presence of FWM noise for both optical channels.

This is more obvious for C = 16 case as compared to C = 32 case as the blocking probability of the proposed ant-based algorithm is approaching ideal case in lower optical channel. The overall results show that the

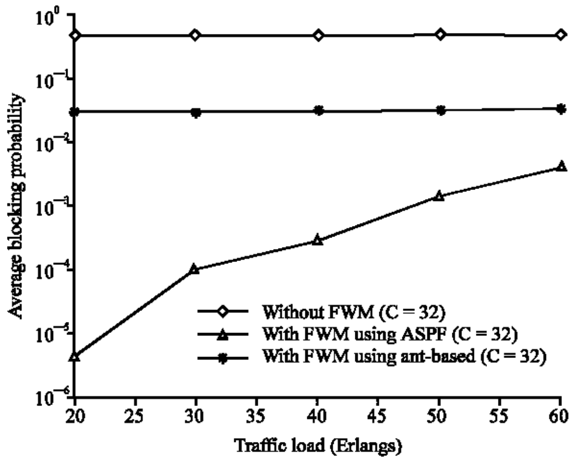

Fig. 5: Blocking probability versus traffic load for C = 32

proposed ant-based algorithm is more efficient and it results in lower blocking probability in both optical channels (C = 16 and C = 32) as compared with ASPF algorithm for the same BER_{min} requirement. Since the number of ants used is equal to the number of optical channels, it is clear that the numbers of ant are necessary to find a good solution in an efficient way for such a problem of a given size is important.

CONCLUSION

In this study, we propose an Ant-based algorithm for FWM-aware wavelength assignment. The proposed ant-based algorithm outperforms the ASPF algorithm in the presence of FWM noise for both optical channels. The performance of the proposed ant-based algorithm is more obvious in C = 16 case as compared to C = 32 case as the blocking probability of the proposed ant-based algorithm is approaching the ideal case in lower optical channel. Generally, careful optical channel capacity selection, low FWM crosstalk power are strongly desired for the accomplishment of efficient, cost-effective, high capacity WDM transparent optical.

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