Avoiding Adjacent Channel Interference in Static RWA

K. Manousakis, K. Christodoulopoulos and E. Varvarigos
Computer Engineering and Informatics Department, University of Patras, Greece, and
Research Academic Computer Technology Institute, Patras, Greece
{*manousak*, *kchristodou*, *manos*}@ceid.upatras.gr

***Abstract*—We design and implement an algorithm for solving the static RWA problem based on an LP relaxation formulation. This formulation is capable of providing integer optimal solutions despite the absence of integrality constraints for a large subset of RWA input instances. In static RWA there is no a-priori knowledge of the channels usage and the interference among them cannot be avoided once the solution has been found. To take into consideration adjacent channel interference, we extend our formulation and model the interference by a set of analytical formulas as additional constraints on RWA.**

***Index Terms*— Routing and Wavelength Assignment, offline traffic, LP relaxation, adjacent channel interference**

I. INTRODUCTION

Optical networks rely on *wavelength division multiplexing* (*WDM*) to efficiently exploit the massive available bandwidth. WDM enables different connections to be established concurrently through a common set of fibers, subject to the *distinct wavelength assignment constraint*; that is, the connections sharing a fiber must occupy separate wavelengths.

The most common architecture utilized for establishing communication in WDM optical networks is *wavelength routing* [8], where data-streams are transmitted through *lightpaths*; that is, all-optical WDM channels, that may span multiple consecutive fibers. In the absence of wavelength conversion, a lightpath must be assigned a common wavelength on each link it traverses; this restriction is referred to as the *wavelength continuity constraint*. However, two lightpaths may occupy the same wavelength, as long as they use disjoint sets of links; this property is known as *wavelength reuse*. Given a set of requested connections, the problem of setting up lightpaths by routing and assigning wavelengths to them, so as to minimize the network resources used or maximize the traffic served, is called the *routing and wavelength assignment* (*RWA*) problem.

The RWA problem is usually considered under two alternative traffic models. *Static Lightpath Establishment* (*SLE*) addresses the case where the set of connections is known in advance and *Dynamic Lightpath Establishment* (*DLE*) considers the case where connection requests arrive randomly, over an infinite time horizon, and are served on a one-by-one basis.

Static RWA is known to be an NP-hard optimization problem. Routing and the wavelength assignment problems are often solved sequentially rather than simultaneously in order to make the problem more computationally tractable. Various efficient heuristics have been lately proposed for both routing [9], [11], and wavelength assignment [11].

The static RWA optimization problem can be considered, in an obvious way, as a special case of the integer multicommodity flow problem with additional constraints, and is formulated as an *integer linear program* (ILP). Typical RWA ILP formulations were initially proposed in [2], [7] and [10]; they contain all required constraints for a general RWA scheme to be valid and aim at minimizing the maximum resource usage, in terms of wavelengths used on network links.

In WDM transparent networks the signal quality degrades subject to physical impairments. Inter-channel crosstalk depends on the utilization of adjacent channels over a path [3], [6]. Moreover, the effects of other impairments, such as cross-phase modulation (XPM) and four-wave mixing (FWM), depend highly on the utilization of the adjacent or the next-to-adjacent channels [1], [5]. To this end, avoiding adjacent channel interference is a key issue in designing transparent WDM networks.

In [3] a crosstalk-aware algorithm for online RWA is presented. The proposed algorithm is based on the enumeration of the crosstalk inducing sources over a path, given that the logical topology (established lightpaths) is known. Other approaches, such as [5] try to avoid four wave mixing and cross phase modulation. However, to the authors' best knowledge, no such approaches have been proposed for the offline – static traffic case.

In this work, we design and implement a new algorithm for solving *static RWA*. The algorithm is based on a (not integer) *linear programming* (*LP*) *formulation*, that was recently proposed in [9]. It is claimed and experimentally observed, that this formulation is able to provide integer optimal solutions (despite its generally non integral nature) for a large fraction of RWA input instances; those that actually do have at least one integer optimal solution among possibly few other fractional ones. In case of a fractional solution, a rounding technique is used. Thus, the algorithm is of approximating nature at a whole, but outputs exact RWA solutions for the corresponding fraction of RWA input instances. Its complexity is dominated by the execution time of LP-solving, which is considered efficient for the great majority of all possible LPs when using Simplex algorithm.

In static RWA there is no a-priori knowledge of the channels usage and the interference among them cannot be

978-1-4244-1876-3/08/$25.00 ©2008 IEEE

avoided once the solution has been found. Thus, contrary to online algorithms such as [3], [5], the interference among channels has to be incorporated in the formulation of the problem. To suppress the adjacent channel interference through the network we model the effect among adjacent channels as additional constraints and incorporate them in our LP formulation. This technique can be extended in a straightforward way so as to penalize interference among specific sets of channels in order to cope with other channel related impairments.

II. RWA PROBLEM

A fixed network topology is represented by a connected, simple graph $G=(V,E)$. V is the set of nodes with routing capabilities. We assume that the nodes are not equipped with wavelength conversion capabilities. The reader is referred to [10] for the changes that are required in the formulation for the cases of sparse or full wavelength conversion. E denotes the set of (point-to-point) single-fiber links. Each fiber is able to support a common set $C=\{1,2,\ldots,W\}$ of W distinct wavelengths.. The static version of RWA assumes an a-priori known traffic scenario given in the form of a matrix of nonnegative integers $\mathbf{\Lambda}$, called the traffic matrix. Then, $\mathbf{\Lambda}_{sd}$ denotes the number of requested connections from source-node s to destination-node d.

The algorithm is given a specific RWA instance; that is, a fixed network topology, its nodes' and links' characteristics and a static traffic scenario. It returns the instance solution, in the form of routed lightpaths and assigned wavelengths, and the blocking probability that accounts for requests that are not served.

The algorithm consists of three phases. The first phase computes a set of candidate paths to route the set of requested connections. The second phase utilizes Simplex algorithm to solve the LP that formulates the given RWA instance. In case of a fractional solution, a rounding technique is used. The third phase, finally, handles the infeasible instances, so that some (since all is impossible) additional requested connections can be established. Infeasibility is overcome by iteratively increasing the number of available wavelengths by 1 and re-executing the second phase. The resulting RWA solution must be converted to a final one that uses only W wavelengths; therefore, some wavelengths must be removed and the lightpaths occupying them have to be blocked. The removed wavelengths are those occupied by the minimum number of lightpaths, so as to block the minimum number of requested connections.

A. RWA Formulation

The proposed LP formulation aims at minimizing the maximum resource usage, in terms of wavelengths used on network links. Let F_l denote the flow cost function, an increasing function on the number of lightpaths traversing link l; the actual formula is presented in the next subsection. Then, the LP objective is minimizing the sum of all F_l values. The following types of parameters, constants and variables are used:

Parameters:

- $s,d \in V$ **:** ingress and egress network nodes
- $w \in C$ **:** an available wavelength
- $l,l' \in E$ **:** network links
- $p \in P_{sd} \subset P$ **:** a candidate path

Constant:

- Λ_{sd} **:** the number of requested connections from node s to node d

Variables:

- λ_{plw} **:** an indicator variable, equal to 1 if path p occupies wavelength w on link l, else 0
- F_l **:** the flow cost function value of link l

Since F_l is a function of the number of lightpaths traversing link l, we have:

$$F_l = f\left(\sum_{p\in P}\sum_{w}\lambda_{plw}\right)$$

LP Formulation

$$\textbf{minimize}: \sum_{l} F_l$$

subject to the following constraints:

- Distinct wavelength assignment,
  $\sum_{p}\lambda_{plw} \le 1$, for all $l \in L$, for all $w \in C$.
- Wavelength continuity constraint,
  $\lambda_{plw} = \lambda_{pl'w}$, for all $p \in P$, for all $w \in C$, for all l and l' consecutive links in path p.
- Demand constraint,
  $\sum_{p\in P_{sd}}\sum_{w}\lambda_{plw} = \Lambda_{sd}$, for all sd, when l is the first link on p
- Flow cost function per link l:
  $$F_l \ge f\left(\sum_{p\in P}\sum_{w}\lambda_{plw}\right) = f\left(W_l\right)$$

As expected, in the ILP formulation we would require the variable λ_{plw} to take values 0 or 1. The integrality constraints are relaxed to $0 \le \lambda_{plw} \le 1$ for all $p \in P_{sd}$, $l \in L$, $w \in C$. This problem is referred to as the ILP relaxed problem.

B. Flow cost function

The flow cost function F_l is used to express the amount of congestion arising on each network link, given a specific routing of the requested connections. To do so we express F_l as a function $f(W_l)$, where W_l is the number of lightpaths crossing link l.

More specifically, let $W_l \le W$ be the number of lightpaths crossing (or the number of wavelengths occupied in) link l. In our notation, we have

$W_l = \sum_p \sum_w \lambda_{plw}$. We choose F_l to be a properly increasing function of W_l. F_l is also chosen to be convex (instead of linear), implying thus a greater amount of 'undesirability', when a single link becomes highly congested.

We utilize the following flow cost function:

$$F_l\left(W_l\right) = \frac{W_l}{W + 1 - W_l}$$

The above (nonlinear) function is inserted to the LP in the approximate form of a piecewise linear function; i.e., a continuous non-smooth function, that consists of W consecutive linear parts. The piecewise linear function is constructed as follows: Set i=1,…,W and begin with $F_l(0)=0$. Then, $F_l^{\,i}(W_l)=a_i \cdot W_l+\beta_i$, $i-1 \leq W_l \leq i$, where $a_i=F_l(i)-F_l(i-1)$ and $\beta_i=(i-1) \cdot F_l(i) - i \cdot F_l(i-1)$.

Observe that the piecewise linear function is exactly equal to the corresponding F_l for each of their integral arguments (Wi=1,…,W) and greater in any other (fractional argument) case. Inserting a sum of such piecewise linear functions to the LP objective, therefore, results in the identification of integer optimal solutions by Simplex, since the vertices of the polytope constructed by the constraints set tend to correspond to the corner points of each piecewise linear function and thus consist also of integer components.

C. *Iterative fixing and rounding technique*

If we do not obtain integers solutions by the LP execution we employ the following iterative fixing and rounding methods. We start by fixing variables, that is making the integer solutions of the previous LP execution constants, and solve the reduced remaining problem. When this process cannot be further pursued we continue with the rounding process. We round a single variable, the one that is closest to 1 and continue solving the reduced LP problem.

Rounding is inevitable in the case that there is no integer solution with the same objective as the LP relaxation of the RWA instance. While fixing variables helps us move to more integer solutions with the same objective, rounding helps us move to a higher objective and search for an integer solution there. Note that if we reach an integer solution only by fixing the variables we are sure that we have found an optimum integer solution. However, by the time that we round a single variable we are not sure anymore that we will find an optimum.

III. INTERFERENCE AWARE RWA

In WDM transparent networks the signal quality degrades subject to physical impairments. These impairments depend on the physical characteristics of the fibers used, but some of them also vary with the network utilization. For example, inter-channel and intra-channel crosstalk, cross phase modulation and four-wave mixing not only depends on the fibers characteristics, but on the utilization of the other wavelengths of the links as well. More specifically, inter-channel crosstalk has to do with the power leaking that occurs between channels that are adjacent (Figure 1). Moreover, cross-phase modulation is more sever in the two adjacent channels and deteriorates as we move away from the examined channel. Finally, four-wave mixing depends on the utilization of certain sets of wavelengths and is more sever if the adjacent channels are active. To this end, avoiding adjacent channel interference is a crucial factor in designing transparent WDM networks.

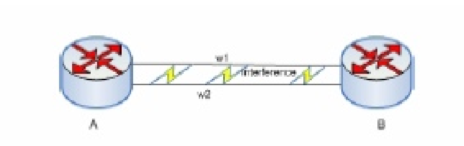

Figure 1: Inter-channel cross-talk interference between two adjacent wavelengths. w_1 carries the signal, and w_2 is the crosstalk interferer.

In the dynamic traffic case, where the connections are established on a one-by-one basis, each time we examine the feasibility of a lightpath we can calculate the effect of the other established lightpaths. In other words, in the dynamic traffic scenario we can always calculate or measure the effect of wavelength interference to the lightpath under examination because the other lightpaths have already been established when the algorithm is executed. However, this cannot be done in the static RWA case, since the utilization of lightpaths form the variables of the problem. Therefore, in this case, we have to consider the interference among channels in the formulation that solves the RWA problem.

In this section, we enhance the LP formulation presented in the previous section to take into consideration the interference among adjacent channels on the same fiber. To do so, we describe the effect of adjacent channel interference with an analytical formula that is additive over the links that comprise the path. Then, we constrain the total adjacent channel interference accumulated over a lightpath so as to be less than a predefined threshold. A similar approach can be adapted in order to constrain the interference among specific channels so as to cope with cross-phase modulation and four-wave mixing effects.

Definitions:

- Distance of two wavelengths: $d\left(w_i, w_{i+1}\right) = d\left(\left|w_i - w_{i+1}\right|\right),\ w_i = \{i\},\ w_i \in C$.
- Adjacent wavelengths: Two wavelengths are called adjacent if the distance between them is $d\left(w_i, w_{i+1}\right) = 1$.
- Interference of two wavelengths in the same link: Two wavelengths interfere with each other if they are adjacent. That is, if the distance between them is 1.

An acceptable optical OSNR level ($OSNR_{min}$) needs to be maintained at the receiver. We impose the constraint of adjacent channel interference inside RWA to be below a predefined threshold for each lightpath, in order to ensure an acceptable OSNR at the destination. To do so we implement the following constraint:

$$\sum_{l\in p}\lambda_{plw_{i-1}}+\sum_{l\in p}\lambda_{plw_{i+1}}+a\cdot\lambda_{pl_jw_i}\le D_{\text{ISI}}+a, \qquad (1)$$

for all $p\in P$ and $w\in C$, where

- a: constant (taking large values, e.g. a=100).
- D_{ISI}: maximum acceptable adjacent channel interference a path can tolerate.
- l_j: first link in path p.
- $\sum_{l}\lambda_{plw_{i-1}}+\sum_{l}\lambda_{plw_{i+1}}$: sum of wavelengths that affect the signal w. Only adjacent wavelengths increase the interference.
- $a\cdot\lambda_{pl_jw_i}=\begin{cases}a, & \text{if } w_i=1\ (\text{active})\\ 0, & \text{otherwise}\end{cases}$

If we further analyze the above cases, we have

1) In case $a\cdot\lambda_{pl_jw_i}=a$, constraint (1) becomes $\sum_{l}\lambda_{plw_{i-1}}+\sum_{l}\lambda_{plw_{i+1}}\le D_{\text{ISI}}$ and the number of wavelengths that affect the signal is actually computed and is constrained to be less than the predefined threshold.
2) In case $a\cdot\lambda_{pl_jw_i}=0$ (the path was not selected and the constraint for adjacent channels must not be taken into account), constraint (1) becomes $\sum_{l}\lambda_{plw_{i-1}}+\sum_{l}\lambda_{plw_{i+1}}\le D_{\text{ISI}}+a$. With a relative big constant a, the inequality is always true and does not affect the RWA solution.

- Extreme cases: if $w_i=1$ then $\lambda_{plw_{i-1}}=0$, and if $w_i=W$ then $\lambda_{plw_{i+1}}=0$.

The following example illustrates the operation of the above formulation (Figure 2 and Figure 3). Assume there is a request from A to E. To serve this request we compute k paths from A to E. A potential path is p={A,B,C,D,E}.

Figure 2 shows the case in which a lightpath from A to E is established over path p and wavelength 2 is selected to serve it. In this case we have to accumulate the interference of adjacent channel introduced at each intermediate link over the whole path. Since wavelength 2 is utilized, $a\cdot\lambda_{pl_jw_i}=a$ for w_i=2 and thus the constraint for this path becomes $\sum_{l}\lambda_{plw_{i-1}}+\sum_{l}\lambda_{plw_{i+1}}\le D_{\text{ISI}}$.

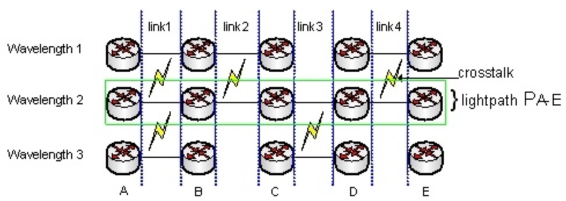

Figure 2: A used wavelength is represented by a line connecting 2 OXCs. Path from A to E uses wavelength 2. Adjacent channel interference is computed as the sum of adjacent used wavelengths over the path, which is equal to 5 in this specific example.

On the other hand, Figure 3 depicts the case that path p is not used and thus channel interference must not be taken into consideration for this path. To this end, for wavelength 2, we have $a\cdot\lambda_{pl_jw_i}=0$ (w_i=2) and thus constraint (1) becomes $\sum_{l}\lambda_{plw_{i-1}}+\sum_{l}\lambda_{plw_{i+1}}\le D_{\text{ISI}}+a$, which holds always provided that we use a large enough constant a. In this way, the utilization of the other channels does not affect the interference constraint of a channel that is not utilized.

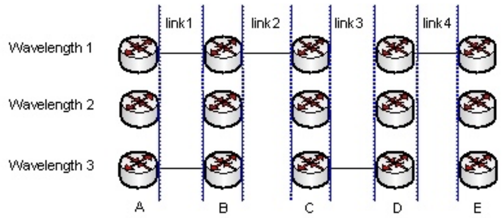

Figure 3: Wavelength 2 is not used. The inequality that constrains the interference induced on the specific wavelength is always true for a relative large values of constant a. Not imposing the constraint is equivalent to know a-priori that wavelength 2 won't be used.

IV. RESULTS

In order to evaluate the performance of the proposed interference-aware RWA algorithm we carried out a number of simulation experiments. We implemented the RWA formulation in Matlab and we used glpk library [4] to solve the LP problem.

The network topology used in our simulations was the NSFnet network presented in Figure 4. Network performance was measured through the use of the average blocking probability of 100 RWA executions corresponding to different random static traffic instances of a given traffic load. More specifically, we define the traffic load as the fraction of the number of the requested connections to the number of the total possible connections. The traffic matrix $\mathbf{\Lambda}$ was created by generating connections with random source and destination nodes, drawn by a uniform distribution, until we reach the given load. By controlling the random seed we were able to produce 100 different instance of the RWA problem for a given traffic load, and reproduce them again for subsequent experiments.

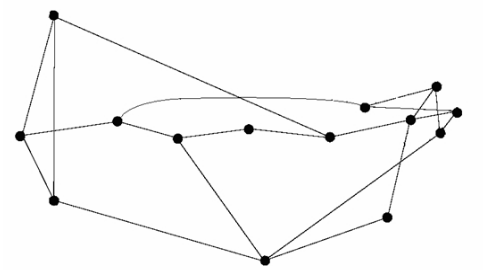

Figure 4: The NSFnet network with 14 nodes and 21 bidirectional links

Figure 5 shows the blocking probability of connections versus the maximum acceptable wavelength-interference a path can tolerate (D_{ISI}). The links utilize at maximum 6 wavelengths and the traffic load is 5%, 10% and 20% of the total number of possible connections. The graph shows that adjacent channel interference affects significantly the blocking performance of the network. The blocking probability reaches 20% in the case of 20% traffic load, if interference among adjacent wavelengths is not at all allowed (D_{ISI}=0). As we decrease D_{ISI}, we make the constraint less stringent by allowing a lower signal-to-adjacent channel interference ratio to be acceptable at the receiver. Therefore, the blocking probability decreases as D_{ISI} increases.

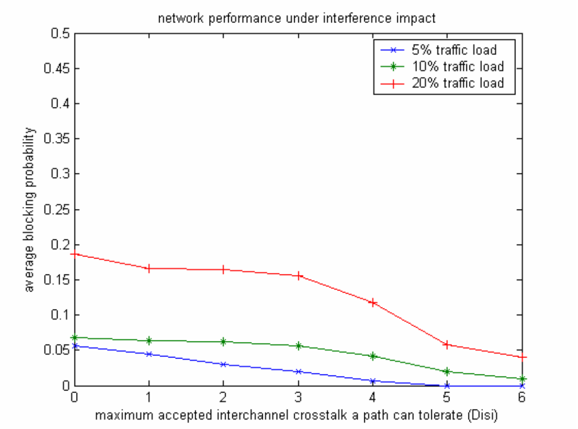

Figure 5: Blocking probability vs. the maximum accepted inter-channel interference a path can tolerate. The links have W=6 available wavelengths.

To evaluate the performance of the proposed algorithm we compared it to that of a typical RWA formulation that considers adjacent interference after the results have been found. In the latter simple RWA formulation, after the solution has been found and the lightpaths to be established are known, we measure the interference among adjacent channels. If a path has interference above the D_{ISI} threshold, the path is rejected. The same procedure is followed until all paths satisfy the D_{ISI} threshold. As can be seen in Figure 6, our proposed interference-aware algorithm provides significant improvements, over the RWA algorithm that does not incorporate interference constraints in the LP formulation.

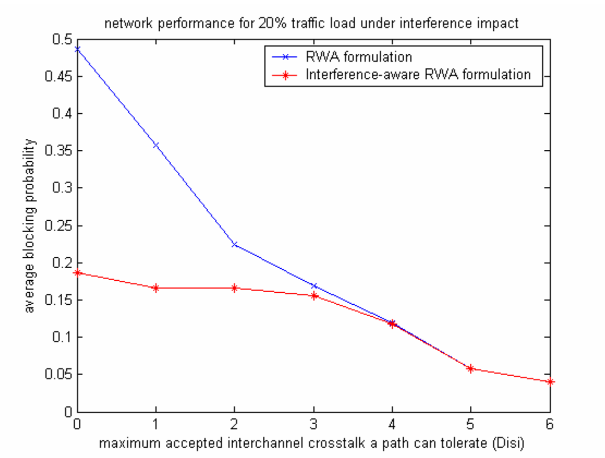

Figure 6: Blocking probability vs. the maximum accepted inter-channel interference a path can tolerate for RWA and interference aware RWA.

As expected, by employing the interference constraint (1) in the LP formulation, the integrality performance deteriorates. In future we plan to perform more simulation experiments, for more complicated topology and traffic scenarios, and comment on the effects of adding the interference constraint in the integrality performance of the algorithm.

V. CONCLUSIONS

We proposed an algorithm for solving the static RWA problem based on an LP formulation. The algorithm provides integer optimal solutions despite the absence of integrality constraints for a large subset of RWA input instances. We then extended the RWA formulation so as to model the adjacent channel interference using a set of analytical formulas as additional constraints on RWA. Our results quantified the blocking performance improvement obtained by the proposed interference-aware RWA algorithm when compared to a typical algorithm that solves the pure RWA and considers interference in the post-processing phase.

ACKNOWLEDGMENTS

This work has been supported by the European Commission through the DICONET project.

REFERENCES

[1] G. P. Agawal, "Fiber-Optic Communication Systems, 2nd ed." New York: Wiley, 1997.

[2] D. Banerjee and B. Mukherjee: "A Practical Approach for Routing and Wavelength Assignment in Large Wavelength-Routed Optical Networks", JSAC, vol. 14, no. 5, pp. 903-908, June 1996.

[3] T. Deng S. Subramaniam and J. Xu: "Crosstalk-Aware Wavelength Assignment in Dynamic Wavelength Routed Optical Networks", Proc. Broadnets, 2004.

[4] http://www.gnu.org/software/glpk/glpk.html

[5] J. He, M. Brandt-Pearce, Y. Pointurier and S. Subramaniam: "QoT-Aware Routing in Impairment-Constrained Optical Networks" IEEE GLOBECOM, pp. 2269-2274, Nov. 2007

[6] J.-G. Hwang et al.: "A RWA Algorithm for Differentiated Services for QoS guarantees in the Next Generation Internet based on DWDM Networks ", Photonic Network Communications, 8:3, pp. 319-334, 2004.

[7] R. Krishnaswamy K. Sivarajan: "Design of Logical Topologies: A Linear Formulation for Wavelength Routed Optical Networks with no Wavelength Changers", IEEE Trans. on Networking, vol. 9, no. 2, pp. 186-198, 2001.

[8] B. Mukherjee, D. Banerjee, S. Ramamurthy and A. Mukherjee: "Some Principles for Designing a Wide-Area WDM Optical Network", IEEE TON, vol. 4, no. 5, Oct. 1996.

[9] A. E. Ozdaglar and D. P. Bertsekas: "Routing and Wavelength Assignment in Optical Networks", IEEE/ACM Transactions on Networking, 11(2), pp. 259-272, 2003.

[10] T. E. Stern and K. Bala: "Multiwavelength Optical Networks: A Layered Approach", Prentice Hall, 1999.

[11] H. Zang, J. P. Jue and B. Mukherjee: "A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks", SPIE/Baltzer Optical Networks Magazine (ONM), vol. 1, no. 1, Jan. 2000.