A NATURALLY INTELLIGENT LIGHTWAVE COMMUNICATION NETWORK

Bhumip KHASNABISH*, Majid AHMADI*, Malayappan SHRIDHAR** and Krishnaiyan THULASIRAMAN†,

*Department of Electrical Engineering, University of Windsor, Windsor, Ontario, Canada, N9B 3P4.
**Department of Electrical and Computer Engineering, University of Michigan-Dearborn, Michigan, 48128, USA.
†Department of Electrical and Computer Engineering, Concordia University, Montreal, P.Q., Canada, H3G 1M8.

ABSTRACT

A new FOUR-LAYER architecture - in contrast to the standard SEVEN-LAYER Open System Interconnection (OSI) structure - for Naturally Intelligent Lightwave-communication Networks (NILINs) is presented. These networks use WDMed (Wave-length Division Multiplexed) optical fibers as transmission media, operate as slotted networks, usually have zone-wise regular topologies, and easily extendable. Furthermore, the bandwidth allocations can be easily harmonized with the terminals demands, and the source-destination separation (in number of hops) can be reduced to as low as one hop by tuning the soft-topology via distributed cut-through effects. These occur because of the networks inherent capability to learn from the nature, i.e., the operating environment (capacity demands, traffic patterns, network status etc.) of the network. This expository paper serves as an introduction to the novel network design and operation, and presents some preliminary results obtained regarding the integrated network access (of new packets) and outgoing link assignment (to the transit packets) schemes which have been investigated.

Indexing Terms: Application of Neuro-computing techniques in telecommunications, Intelligent networks, Lightwave networks, Learning in telecommunication networks, Supra-high-speed packet switching networks, Telecommunications, Wide area networks.

1. Introduction

With the availability of economically feasible optical fibers as transmission media [1-3, 5, 15], the network designers are endowed with abundant bandwidth to trade it off with nodal buffer requirement [8], nodal complexity [14] etc. Furthermore, with todays technology, the achievable transmission speed in lightwave links is so high that the software-dominated layers of the standard seven-layer OSI architecture (of the ISO) present real bottleneck to the communicating Terminal Equipments (TEs). Therefore, our proposal of four-layer architecture (**Fig.1**) is directed towards performing as much *on-line functions* as possible in hardware. Note that most of the *software controlled processing* (i.e., protocols) overheads include the tasks of:

(i) Scheduling, i.e., channel management, path selection, etc. for both network access control and transit packet forwarding, etc. When the soft-topology of the network is regular, the information about network interconnection can be easily computed, i.e., there is no need to store them at the nodes. We propose such a regular architecture, as was used in [13, 14] for NILiNs.

(ii) Encryption and decryption of messages for preventing active or passive tapping. When optical fibers are used as transmission media, it is very difficult to tap the signal without being detected [18].

(iii) Buffering of packets at the intermediate nodes. When deflection routing [14] is used, the communication channels can be used as effective buffers.

(iv) Retransmission of erroneous or dropped packets. When the network nodes are equipped with buffer stealers, the probability of retransmission may be reduced [10].

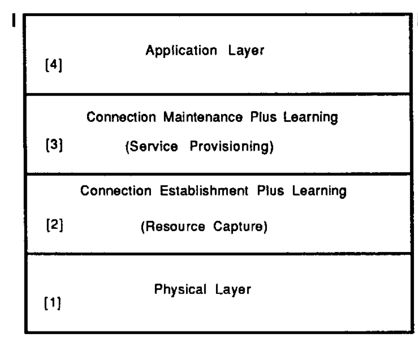

Fig.1 - The proposed four-layer protocol architecture.

The design approach presented in this paper make extensive use of the emerging fine-grained WDM (**W**avelength **D**ivision **M**ultiplexing) technology [1-3, 5, 15] which allows us to construct easily extendable, zone-wise regular network structures. Furthermore, the channel capture and capacity capture can be achieved at the expense of nominal overheads in the proposed networks compared to the previous designs. This feature of NILiNs can be attributed to its capability to learn from the nature, i.e., the operating environment (capacity demands, traffic patterns, network status etc.) of the network.

The remainder of this paper is organized as follows. Section 2 presents an overview of the network architecture. Then we present a glimpse at the mathematical foundations of the proposed networks. Traffic processing algorithms and simulation results are presented in sections 4 and 5, respectively. Some concluding remarks are made in section 6.

 CH2980-1/91/0000-1050 $1.00 © 1991 IEEE

2. Overview of Network Architecture

NILiN operates as a slotted network. At the beginning of each slot, a node receives *at most* 9 packets to route them to the 9 out ports according to the operating traffic processing algorithm (discussed later). The architecture of a 10-node NILiN is as presented in **Fig.2**. Note that, the interconnection structure can be visualized (details are discussed in [11]) as superposition of two bi-directional Manhattan Street Networks (MSNs) [6, 13] where one MSN is placed onto the other at an angle of 45^o. None of the MSNs is, however, necessarily have complete interconnection as dictated by the algebraic formulations of the topology [14]. This is because in NILiNs attempts are always made to circulate the spare channels around the most frequently communicating user groups [11].

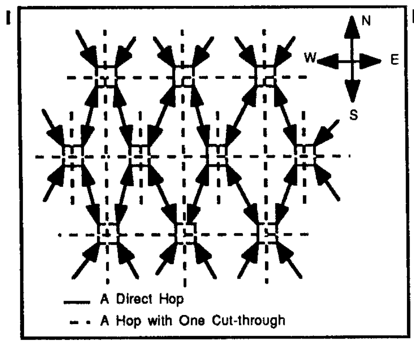

Fig. 2 - The topology of a 10-node (i.e., N=10) NILiN.

Although in lightwave communication networks the optical fibers provide uni-directional packet transmission path from a node to another, the edges in NILiNs are bi-directional. That is, when two nodes are connected, there exists two fiber paths (transmitting traffics in opposite directions) between them. **Fig.2** also shows that the in-degree and out-degree of every node of NILiN are same, where the degree of a node can vary from 3 to 9 depending on its location in the network. The nodes along the periphery of the network have some unused *bi-directional ports* which guarantees that the network can evolve easily without affecting the input/output balance of the nodes.

Addition of nodes to NILiNs is very simple. We find [11] that addition of nodes in groups of fours is more feasible (performance wise) than adding one node at a time. This not only helps to maintain the regularity of the network, but also provide some bonus paths to the existing nodes.

NILiN is highly fault-tolerant, because of its following features: • It is highly interconnected, • It keeps the unused channels circulating around the frequently communicating nodes, • Failure of an edge of NILiN puts a bi-directional port out of operation, therefore, the in-degree and out-degree of the node still remain same, although it is decreased by one, • Failure of a node puts all the incoming and outgoing channels of that node out of operation, the neighboring nodes, however, can still communicate using the other direct/indirect channels as can be clearly seen in **Fig.2**, • The number of nearest (i.e., 1-hop-away nodes) neighbors in NILiNs is 8, which is much higher than that in the original MSNs.[13, 14].

Note that, the flexibility of interconnection among the nodes in NILiNs can be attributed to the current availability of wavelength tunable transmitters and receivers [1-3, 5]. Thus, wavelength reuse becomes feasible. The maximum number (defined as the ratio of the total tuning range to the minimum channel spacing required to guarantee minimum level of cross-talk degradation) of channels that can be accommodated per link is determined by the tunable filter technology. Both electrical tuning (electro-optic filters) and acoustical tuning (acousto-optic filters) are possible [1]. Although it is very slow, temperature based tuning can also be performed [1].

If the period for which a particular channel remains captured by a transmitter/receiver is very small, fast tuning is mandatory, otherwise slow tuning (e.g., temperature based tuning) can also be safely employed without degrading system performance.

Routing of packets in NILiNs is performed using source routing algorithms as was originally proposed for MSNs [14]. The intermediate nodes forward the packets on the basis of the Routing Information (**RI**) and globally unique destination address (as computed using polar co-ordinate system [11]) at the packet's header using the recently proposed [10] neural Distributed Associative Memory (**DAM**) at the nodes. In [11] it has been shown that fast learning and direct access to the learned switching pattern is also possible.

3. A Glimpse at the Mathematical Foundation

The proposed architecture of NILiN (see **Fig.2**) can be viewed as superposition of two Directed Graphs (**DGs**), G = (V, E) - not to be confused with the superimposed MSNs equivalence - one carrying Top-Down (**TD**) traffics and the other carrying Bottom-Up (**BU**) traffics. Note that, the vertices are $V = \{v_i : i=1, 2, ...\}$ and the directed edges (optical fiber links) are $E = \{e_{jk} : j, k = 1, 2, ... \}$. The BU-DG contains directed links emanating from the bottom layer towards the adjacent upper layer nodes and the TD-DG contains directed links emitting from the top layer nodes towards the neighboring lower layer nodes. It can be also seen that the network can grow easily in all four (north, south, east and west) directions, where the effect of growth is the same as that of cascading a layer of nodes in any one or more of the aforementioned directions.

The dynamics of both the TD- and BU-DGs can be represented by the following system of coupled differential equations [4]:

$$\frac{dx_i(t)}{dt} = -\alpha_i x_i(t) + \sum_{m=1}^{n}[\beta_m x_m(t - \tau_{mi}) c_{mi}(t)] - \sum_{m=1}^{n}[x_m(t - \tau_{mi}) q_{mi}(t)] + I_i(t). \qquad (1)$$

$$c_{jk}(t) = \frac{p_{jk} z_{jk}(t)}{\sum_{m=1}^{n}[p_{jm} z_{jm}(t)]} \qquad (2)$$

$$\frac{dz_{jk}(t)}{dt} = -u_{jk} z_{jk}(t) + [\beta_k x_j(t - \tau_{jk}) x_k(t)] \text{ if } p_{jk} > 0 \qquad (3)$$

where $\sum_{m=1}^{n} p_{jm} = 0$ or 1, and I_i, α, β and u_{jk} are non-negative activity control parameters. Note that, i, j, k = 1, 2, ..., N. $x_i(t)$ describes the state of the i-th active Terminal Equipment (TE) at time t. Note that, an active TE can be in either silent state or burst state. $z_{jk}(t)$ is the captured channel capacity (i.e., the number of WDMed channels) from the j-th node to the k-th node. The magnitude of $z_{jk}(t)$ is controlled by T_{jk} (the tuner of the directed link e_{jk}, i.e., the synaptic knob, which happens to be a geometrically distributed random number generator, to be implemented in hardware [17], as found in [11]) by cross-correlating the activity received form the j-node to the locally generated activity, i.e., $x_k(t)$. $c_{jk}(t)$ is just the normalized version of the $z_{jk}(t)$, as can be seen from (2).

Equation (1) shows that the activity at the i-th node, i.e., $x_i(t)$, decays at rate $\alpha_i x_i(t)$, grows at a rate of $I_i(t)$ under the influence of external environment, and because of packet sinking at that node, a certain amount of channel capacity is released to the available channel pool of that node, and finally this node captures a definite amount of channel capacity to forward the resulting traffics. Equation (3) depicts that $z_{jk}(t)$ decays at a rate of $u_{jk}\, z_{jk}(t)$, and increases by an amount which is controlled by the cross-correlation of the received and locally generated activities.

Since $x_i(t)$ determines *when* the channel(s) is(are) to be captured, mathematically speaking, its value is proportional to the probability that a non-zero number of arrival will occur during a period of τ, i.e., $(1 - e^{-\lambda\tau})$, where $(1/\lambda)$ is the mean inter-arrival time of packets at a node. And, since $z_{jk}(t)$ determines *how much* channel capacity will have to be captured, assuming that each generated burst of an active TE contains a geometrically distributed number of slots (defined as the basic unit of time of operation for the network) of packets, we find [11] that $z_{jk}(t)$ needs to be proportional to the value of $[1/(1-b)]$, where b is the probability that the size of the generated burst exceeds one slot.

Finally, in [11], it has also been shown that NILiN learns a route, i.e., a space-time pattern as a concatenated spatial pattern. Both on-line and off-line teachings are possible. Note that, as the number of nodes over a geographic area increases, the more diverse becomes the way of achieving a *path completion* (i.e., packet delivery to the destination). After a route is learned, a supra-threshold activity in a single control vertex (i.e., a source node) can initiate an arbitrarily complicated *spatio-temporal pattern* (i.e., a path).

4. Traffic Processing Algorithms

We consider a 10-node NILiN (**Fig.2**), where each node has a maximum of NINE - including the local source and sink links - input and output links (see **Fig.3**). NILiN operates as a slotted system, and hence once in every slot period a routing decision is made at every node for *at most* EIGHT transit packets, the 9-th packet is from the local source. We define TWO categories (class-A and class-B) of user TEs, as in FDDI networks [18]. The **class-B** TEs include data terminals and lower priority voice terminals; these TEs do not have the authority to modify (i.e., change or update) the values of any of the Routing Information (RI) in the header of the packets generated by them. That is to say, when a class-B TE launch a packet into the network, the RI field of that packet contains the *default* values [11]. Class-B terminals are expected to be very simple and cheap TEs. **Class-A** TEs may include any higher priority terminals (e.g., video TE, sophisticated Voice TE etc.) which have the capability to modify the default RI in the packets header in order to allow them to compete favorably with other transit packets. These terminals are usually moderately complex and expensive, and they might have larger (compared the class-A TEs) number buffers to facilitate buffer stealing [10] by the lower priority transit packets.

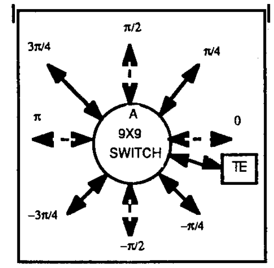

Fig. 3 - Structure of a node of NILiN

About the local packet's access - for class-B stations - to the network, we have the following comments. It is now well-known [7,10] that the transit packets should always be given higher priority over the locally generated packets at a node. This not only reduces the probability of livelocks in the network but also reduces the Mean packet Transfer Time (MPTT). Furthermore, even when an output channel is available, the local packet may not be willing to avail the opportunity to put the packet into the network because the offered channel may not be the desired one. These access control strategies have been considered in the context of the MSNs in [7] and for NILiNs in [11].

Complexity of the processing of network packets in NILiNs depends on whether the node which is processing the packets is a virgin, an expert or an experienced one. The node needs to perform *at most* the following TWO operations before it decides on which input packet gets assigned to which output port: (i) Computation of the address of the next desirable node form the algebraic formulation of the topology and the source, destination and current node addresses, and (ii) Threshold-based determination of priority to select the best candidate for each of the outgoing port. These two operations are discussed in details in [11].

Routing with virgin or naive nodes is equivalent to random routing. This is because, at the beginning of every slot the node checks the desired output port for each of the packets in the input port, routes the non-conflicting packets to the desired out ports and the *conflicting packets* are *randomly assigned* to the remaining outgoing port. As expected, the delay performance of this type of routing is the worst of the three schemes considered (see **Fig.4**) since the nodes are really very simple and dumb in this case.

With the incorporation of some expertise in the nodal processing of network packets, the nodal structure becomes a little bit complicated [11]. The nodal operating system contains a set of pre-specified rules to resolve the conflicts among the input packets which are competing for the same outgoing port. The RI in this case may contain Routing Preference Vector (RPV) along with other information like number of deflections suffered, distance of destination from the current node, etc. as considered in [7,14]. The RPV contains the address of at least TWO possible out ports as can be dictated by two different routing orientations. Note that with the nodal structure of **Fig.3**, SEVEN different orientations are possible ($[\pm n\,\pi/4]$, where n=1, 2, 3, 4). At this point, it is worth mentioning that the $\pm\pi/2$ routing implements optimal routing in bi-directional type MSNs. We find [11] that there exists a very interesting relationship between the skewness (i.e., non-uniformity) of traffic distributions and the parameter *n*.

Finally, when the network contains *experienced* nodes, it can be assumed that the nodes have *learned* to maintain input port to output port connection in a switch based on the observation of the RI (including the RPV) of the previous e.g., hundred packets. Consequently, the arrivals find pre-arranged connections to the out ports. It has been observed [11] that the best result is obtained when a pre-set connection remains intact for a geometrically distributed number of slots of time.

The parameter of this distribution depend on the source-destination pattern, and hence this parameter is to be learned from the environment, i.e., the operating conditions of the network. Note that in a 10-node network, the total number of source-destination patterns are $2\mathrm{x}\binom{10}{2}$ = 90. In the next section, we present simulation based comparison of packet routing techniques in NILiN where all the nodes can be either virgin or expert or experienced. **The network with *experienced* nodes provides the best performance.**

5. Simulation Results

The performance of the proposed traffic processing techniques have been investigated [11] using an exact simulation of a 10-node NILiN (**Fig.2**). We have considered all three types (i.e., virgin, expert and experienced) of nodes to compare the packet transfer delay related performance of the network. Structure of a node with orientation of different incoming and outgoing links are as shown in **Fig.3**. In the simulation, the topology is defined using algebraic formulations developed in [11] in polar co-ordinate system, and the Mean Packet Transfer Time (MPTT) is measured in units of hop-counts as has been done previously [7,10]. One hop-count is equal to the sum of propagation and transmission times for one hop and the processing delay (queueing delay, if any, plus the time needed for making routing decision etc. at one end of the hop). A source node selects a destination node by tossing a 9-sided (for a 10-node network) *fair dice*, and Poisson process was used to model arrivals from a TE to the network. Although the results presented in **Fig.4** are for a 10-node NILiN, they can be considered as representative of other simulated network sizes as well [11].

The topological properties of NILiNs are found using both simulation and analytical techniques. The analytical results are in direct agreement with those obtained by simulation. We use the method proposed in [9] to develop analytical expressions for topology z-transform, T(z), Inter-Node Distance (IND) distribution, Mean IND (MIND), etc. It has been found [11] that for a 10-node NILiN, $T(z) = [(1 + 3z + 3z^2 + 3z^3)/10]$, where e.g., the term $3z^2$ indicates that there exists 3 (the coefficient of z^2) nodes in the network which are 2 (the exponent of z) hops away from an arbitrary source in the network (note that the architecture of NILiN can be considered to be a Symmetric Interconnection Network (SIN) [14]). Therefore, the IND distribution for the network under consideration is: $N_0=1$, $N_1=3$, $N_2=3$, $N_3=3$, where N_i represents the number of nodes i-hop away from the source. The diameter of a 10-node NILiN is 3 hops, since the highest exponent of z in the equation for T(z) is 3, and its MIND is 1.8 hops (since $\left.\frac{dT(z)}{dz}\right|_{z=1}$ is defined as the mean IND for the network), which is proportional to the MPTT at zero load. Consequently, the normalization constant for the delay values presented in **Fig.4** is also proportional to 1.8. Furthermore, since the network uses bi-directional hops, the maximum deflection penalty is bounded by 2 hops.

Fig.4 compares the overall mean delay performance of a 10-node NILiN with different types of nodes. The improvement of network performance - when experienced nodes are employed - is visibly distinct. The main reason for this improvement is the *highly adaptive* nature of the network *access assignment and transmission capacity allocation* which are the most desirable features of a network operating system.

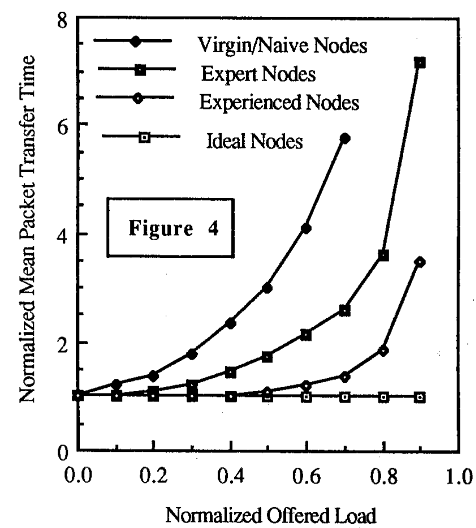

Fig. 4 - Variation of the Normalized Mean Packet Transfer Time (MPTT) with the Offered Load in a 10-Node NILiN for Different Types of Nodes. Note that when the Nodes are Virgin, they Forward Packets in a Random Fashion, when they are Expert, Packet Forwarding Occurs on the Basis of Pre-specified Rules, and when the Nodes are Experienced, Traffic Processing is Performed on the Basis of Learned Rules.

6. Conclusions

We have proposed a novel lightwave network architecture which uses the emerging fine-grained WDMed channels for internode communication. The access assignment and transmission capacity allocation are highly flexible (since the nodes can be taught) in these networks which make them very attractive for future multi-service communications.

The advantage of packet routing using experienced network nodes - rather than using expert nodes - is so obvious (from **Fig.4**) that it does not need any further explanation. It is worth noting that with virgin/naive nodes, the nodal operating system of the network practices random routing, with expert nodes routing is performed using a certain set of rules (e.g., those used in [7,14]). These rules are designed to reduce the number of deflections, to give higher priorities to those packets which are closer to destination, etc. [10,14]. With experienced nodes, the nodal operating system learns (on-line) to adjust both channel assignment and capacity allocation to local and transit packets based on network status and its running conditions, and hence this scheme outperforms all the previously proposed packet routing methods. The moral of the story is "Practice makes a node perfect".

Finally, we believe that the results presented in this paper will generate vigorous enthusiasm among the researchers in network designs, maintenance, operations, etc. Because, the incorporation of natural intelligence in network operating system not only renders network operation efficient but also helps to maintain the pre-specified Grade-Of-Service (GOS) even during the most unexpected network conditions, e.g., sudden load surge as in the Christmas day, isolated node or link failure, zonal network black-out due to earthquake or any other *natural* disaster, etc.

Acknowledgements

The authors are grateful to Dr. Shervin Erfani of AT&T Bell Labs. for many fruitful discussions. Financial assistance for this research has been provided by the NSERC, Canada, and the University of Windsor, Ontario, Canada.

References

[1] N. K. Cheung, K. Nosu and G. Winzer, Guest Editors, "Dense Wavelength Division Multiplexing Techniques for High Capacity and Multiple Access Communication Systems", *IEEE Journal on Selected Areas in Communications (J-SAC)*, Vol. 8, No. 6, August 1990, pp.945-1220.

[2] P. A. Davies, D. W. Faulkner and M. Koyama, Guest Editors, "Fiber Optic Local and Metropolitan Area Networks", *IEEE Journal on Selected Areas in Communications (J-SAC)*, Vol. 6, No. 6, July 1988, pp.901-1032.

[3] M. S. Goodman, "Multiwavelength Networks and New Approaches to Packet Switching", *IEEE Communications Magazine,* Volume. 27, No. 10, Oct. 1989, pp.27-35.

[4] S. Grossberg, Editor, "**Neural Networks and Natural Intelligence**", A Bradford Book, The MIT Press, Cambridge, MA, USA, Fourth Printing, 1989.

[5] C. K. Kao, Guest Editor, "IEEE LCS: The Magazine of Lightwave Communication Systems", Vol. 1, No. 2, May 1990, pp. 1-75.

[6] B. Khasnabish, "Topological Properties of Manhattan Street Networks", *IEE Electronics Letters,* Vol. 25, No. 20, Sept. 28, 1989, pp.1388-1389.

[7] B. Khasnabish, "An Analytical Technique for Evaluating Packet Routing Policies in Metropolitan Area Networks", *Proceedings of the IEEE Global Telecommunications Conference*, Dallas, Texas, Nov.27-30, 1989, pp.1030-1035.

[8] B. Khasnabish, M. Ahmadi, M. Hlynka, and M. Shridhar, "*SC-TC Tradeoff in High-Speed Packet Switching Networks*", Technical Report, Department of Mathematics and Statistics, University of Windsor, Ontario, Canada, WMR-08, August 1990.

[9] B. Khasnabish, M. Ahmadi, S. Erfani and M. Shridhar, "A New Method for Evaluating Lightwave Network Architectures", To appear in the *Proceedings of the 34-th Midwest Symposium on Circuits and Systems*, Monterey, CA, USA, 1991.

[10] B. Khasnabish, M. Ahmadi and M. Shridhar, "Congestion Avoidance in Large Supra-High-Speed Packet Switching Networks Using Neural Arbiters", Technical Report, Department of Electrical Engineering, University of Windsor, Ontario, Canada, 1991.

[11] B. Khasnabish and M. Ahmadi, "Design and Evaluation of **N**aturally **I**ntelligent **L**ightwave-communication **N**etworks (**NILiNs**)", Technical Report, Department of Electrical Engineering, University of Windsor, Ontario, Canada, 1991.

[12] M. Malek and S. Erfani, Guest Editors, "Service Provisioning in Future Networks", Special issue of *IEEE Network: The Magazine of Computer Communications*, Vol. 4, No. 1, January 1990, pp.1-48.

[13] N.F. Maxemchuk, "The Manhattan Street Network", *Proceedings of the IEEE Global Telecommunications Conference*, Dec., 1985, pp.255-261.

[14] N. F. Maxemchuk, "Routing in the Manhattan Street Network", *IEEE Transaction on Communications*, Vol. 35, No. 5, May 1987, pp.503-512.

[15] S. R. Nagel, "Optical Fibers - the Expanding Medium", *IEEE Communications Magazine*, Vol. 25, No. 4, April 1987, pp.33-43.

[16] E. C. Posner, Guest Editor, "Neural Networks in Communications", *IEEE Communications Magazine*, Vol. 27, No. 11, Nov. 1989, pp.1-108.

[17] R. A. Schulz, "Random Number Generator Circuit", IBM Patent No. 4, 905, 176, *IBM J. Res. Develop*, Vol. 34, No. 5, Sept. 1990, p.792.

[18] A. S. Tanenbaum, "**Computer Networks**", Second Edition, Prentice-Hall Inc., Englewood Cliffs, NJ, USA, 1988.