# STUDIES ON IMPAIRMENT AWARENESS, POWER ECONOMY AND SURVIVABILITY IN OPTICAL NETWORKS

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# STUDIES ON IMPAIRMENT AWARENESS, POWER ECONOMY AND SURVIVABILITY IN OPTICAL NETWORKS

by

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**Dedicated to my father, mother and wife, whose blessings always guide me!**

**Rahul Jashvantbhai Pandya**

# CERTIFICATE

This is to certify that the thesis entitled "**Studies on Impairment Awareness, Power Economy and Survivability in Optical Networks"** being submitted by **Mr. Rahul Jashvantbhai Pandya** to the Bharti School of Telecommunication Technology and Management, Indian Institute of Technology, Delhi, for the award of degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by him. He has worked under our supervision and guidance. The thesis, in our opinion has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.


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# ABSTRACT

In this thesis, we have proposed several solutions to achieve the Impairment Awareness (IA), Power Economy (PE), Survivability and Reliability in Optical Wavelength Division Multiplexing (WDM) networks. In order to overcome the effects of Physical Layer Impairments (PLIs), we have designed and implemented the Impairment Aware-Routing and Wavelength Assignment (IA-RWA) Algorithms, which introduce IA without deploying additional regenerators. The first is IA-RWA with Distributed Light-Path Monitoring (DLPM)-modules, the second is IA-RWA with Dynamic Channel Spacing (DCS) and the third is IA-RWA with Curtailed Bandwidth Allocation (CBA). The proposed IA-RWA algorithms show substantial increase in the IA. Moreover, we also present an experimental demonstration of an impairment aware automatic light-path switching, which also shows a significant improvement in IA.

In order to increase IA, commercial service providers are deploying the regenerators to reduce the noise accumulated by PLIs. This increases the power and capital cost of the networks. On the other hand, to achieve the PE, optical transparency is required. Hence, there is a trade-off between IA and PE. In order to provide the simultaneous increase in IA and PE, we have optimized the selective usage problem of Traffic Grooming-Mixed Regeneration-All Optical Wavelength Conversion (TG-MR-AOWC) using Integer Linear Programming (ILP) and heuristic approaches. The application of TG-MR-AOWC is also evaluated using OptSim Matlab hardware co-simulation. Moreover, we also present an experimental demonstration of an automatic AOWC to increase the IA and PE together.

Since the WDM networks carries high-speed services, it becomes essential to provide survivability against the link and light-path failures. Hence, Survivability and Reliability are also important issues along with IA and PE. In this thesis, we present an application of three well known algorithms to increase the survivability along with IA and PE. The first is Kruskal's minimal weighted topology search algorithm. The second is Hamiltonian cycle (H-cycle) based survivable topology search algorithm and the third is *k*-survivable topology search algorithm. Moreover, we also present the terminal-to-terminal (terminal) reliability study for the survivable topologies. The terminal reliability values for the survivable topologies helps the service providers to choose an appropriate survivable topology to restore the traffic.

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# LIST OF ABRIVIATION

| | |
|---|---|
| ADMs | Add Drop Multiplexers |
| AOWC | All Optical Wavelength Conversion |
| APD | Avalanch Photo Detector |
| API | Application Programming Interfacing |
| ASE | Amplifier Spontaneous Emission |
| BER | Bit Error Rate |
| CBA | Curtailed Bandwidth Allocation |
| CD | Chromatic Dispersion |
| CIC | Client Interface Cards |
| CLP | Connection Loss Probability |
| DCA | Digital Communication Analyzer |
| DCM | Dispersion Compensation Module |
| DCS | Dynamic Channel Spacing |
| DFB | Distributed Feedback Laser |
| DLPM | Distributed Light-Path Monitoring |
| DSF | Dispersion Shifted Fiber |
| DWDM | Dense Wavelengh Division Multiplexing |
| EDFA | Erbium Doped Fiber Amplifier |
| EIA-RWA | Energy Impairment Aware-Routing and Wavelength Assignments |
| ES | Electrical Switching |
| FEC | Forward Error Correction |
| FIT | Failures In Time |

| | |
|---|---|
| FWM | Four Wave Mixing |
| GE | Gigabit Ethernet |
| GMPLS | Generalized Multi Protocol Label Switching |
| GR | Grooming |
| H-cycle | Hamiltonian-cycle |
| IA | Impairment Awareness |
| IA-RWA | Impairment Aware-Routing and Wavelength Assignment |
| ICT | Instrument Control Toolbox |
| ILP | Integer Linear Programming |
| ISI | Inter Symbol Interference |
| ITU | International Telecommunication Union |
| LCD | Liquid Crystal Devices |
| LCoS | Liquid Crystal on Silicon |
| LDCF | Length of Dispersion Composition Fiber |
| LDs | Laser Diodes |
| LIC | Line Interfacing Card |
| LIs | Linear Impairments |
| MEMS | Micro-Electro-Mechanical Systems |
| MLR | Mixed Line Rate |
| MR | Mixed Regeneration |
| NDSF | Non-Dispersion Shifted single-mode optical Fiber |
| NF | Noise Figure |
| NLIs | Non-Linear Impairments |

| | |
|---|---|
| NRZ-PRBS | Non Return to Zero-Pseudo Random Binary Sequence |
| OADM | Optical Add Drop Multiplexers |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OOK | On Off Keying |
| OPEX | Operational Expenditure |
| O-E-O | Optical-Electrical-Optical |
| OS | Optical Switching |
| OSNR | Optical Signal to Noise Ratio |
| OTN | Optical Transport Network |
| OUT-k | Optical Transport Unit-k |
| OXC | Optical Cross Connect |
| PD | Photo Detector |
| PDL | Polarization Dependent Losses |
| PE | Power Economy |
| PIN | p–i–n photodiode |
| PLC | Planar Lightwave Circuits |
| PLIs | Physical Layer Impairments |
| PMD | Polarization Mode Dispersion |
| PRBS | Pseudo Random Binary Sequence Generator |
| Q-factor | Quality-factor |
| QoS | Quality of Service |
| QoT | Quality of Transmission |
| RailTel | 19-node Indian Railway network |

| | |
|---|---|
| RCR | Regeneration and Conversion Rack |
| ROADM | Reconfigurable Optical Add Drop Multiplexer |
| RWA | Routing and Wavelength Assignment |
| SBS | Stimulated Brillouin Scattering |
| SDH | Synchronous Digital Hierarchy |
| SLA | Service Level Agreements |
| SLR | Single Line Rate |
| SNR | Signal to Noise Ratio |
| SOA | Semiconductor Optical Amplifier |
| SONET | Synchronous Optical Network |
| SP | Shortest Path |
| SPM | Self Phase Modulation |
| SRS | Stimulated Raman Scattering |
| TC | Transponder Card |
| TDS 2024 | Digital Storage Oscilloscope |
| TG | Traffic Grooming |
| TGC | Traffic Grooming Cards |
| TR | Terminal Reliability |
| USB | Universal Serial Bus |
| USNet | 24-node United States's Network |
| VISA | Virtual Instrument Software Architecture |
| WAA | Wavelength Assignment Argument |
| WDM | Wavelength Division Multiplexing |

| | |
|---|---|
| XPM | Cross Phase Modulation |
| XT | Crosstalk |

# LIST OF SYBOLS

| | |
|---|---|
| *A* | weight matrix comprised of power costs |
| *C* | connectivity matrix |
| $C_{i,j,w}$ | channel capacity of a light-path between a node pair *(i, j)* on wavelength $w \in W$ |
| *Cost* | distance matrix |
| $C_{Thr}$ | average channel capacity threshold of a link, below, which the link is assumed to be failed |
| $D_c$ | dispersion coefficient |
| *(d)* | destination |
| *E* | set of links |
| $E_k$ | $k^{th}$ fiber link |
| $F_{i,j}$ | number of fibers used on link *(i, j)* |
| *G (V, E)* | network topology with nodes *(V)* and links *(E)* |
| *GR* | grooming |
| *H1 to H8* | H-cycles |
| *L* | link matrix |
| $\left(L_{a,b}^{i,j}\right)_W$ | the number of light-paths between node pair *(i, j)* routed through the physical fiber *(a, b)* on *(w)* $\epsilon$ *W* |
| *l* | parallel phortest paths |
| *N* | number of nodes |
| $N([V_k])$ | neighbor nodes for the selected node $V_k$ |
| $P^{s,d}$ | the total power cost from *(s)* to *(d)* |

| | |
|---|---|
| $P_{AOWC}^{s,j,d}$ | the power cost of AOWC while traversing from *(s)* to *(d)* |
| $P_{i,j}$ | the power cost of a link between a node pair *(i, j)* |
| $P_{margin}^{max}$ | the maximum permitted power margin |
| $P_{OXC}^{s,j,d}$ | the power cost of an intermediate OXC while traversing from *(s)* to *(d)*, where *(j)* indicates intermediate nodes |
| $P_{pR}^{s,j,d}$ | the power cost of used 1R, 2R or 3R while traversing from *(s)* to *(d)*. Where p is an integer, indicating the type of the regenerator (p ∈ [1, 2 and 3]) |
| $P_{rx}$ | the power costs of the receiver |
| $P_{TG}^{s,j,d}$ | the power cost of TG at an intermediate node while traversing from *(s)* to *(d)* |
| $P_{th}$ | the power threshold for an amplification |
| $P_{tr}$ | the power costs of the transmitter |
| $Q_{i,j,w}$ | the Q-factor of a light-path established on wavelength w, between a node pair *(i, j)* |
| $Q_{Thr}$ | thrashold Q-factor |
| $Q_{w}^{s,lp,d}$ | end-to-end Q-factor for a light-path *($l_p$)* on wavelength *(w)* from *(s)* to *(d)* |
| $R([V_k])$ | set of reachable nodes for a selected node $V_k$ |
| *Rx* | Receiver (PIN detector) |
| $R_X$ | is the reliability value of the corresponding component *X*, which are multiplexers, de-multiplexers, TC, OXC, EDFA, 2R, 3R, AOWC, fiber and DCF |

| | |
|---|---|
| $S_o$ | dispersion slope parameter |
| *(s)* | source |
| $T$ | monitoring interval |
| $Tx$ | transmitter |
| $V$ | set of nodes |
| $W$ | set of wavelength |
| $A(E)$ | weight factor of the link $E$ |
| $A_g(E_k)$ | weight factor of the link $E_k$ |
| $A_g(E_{k+1})$ | weigth factor of the link $E_{k+1}$ |
| $\omega_n$ | Carrier frequency number $n$ |
| $x^{s,d,w}$ | an integer variable indicating the number of connections between *(s)* and *(d)* using *(w)* |
| $\delta_{pR,j}^{s,j,d}$, $\delta_{TG,j}^{s,j,d}$ and $\delta_{AOWC,j}^{s,j,d}$ | the binary variables equal to 1, if the pR (MR), TG or AOWC are used (eg. $\delta_{TG,j}^{s,j,d} = 1$ if $TG = j$), otherwise their values remain 0 |
| $\delta_{lp,k}^{s,d,w}$ | the binary variable equal to 1 if the wavelength *(w)* of fiber *(k)* is used to assign a light-path *($l_p$)* between *(s)* and *(d)*, otherwise it remains 0, where $k \in F_{i,j}$ |
| $\delta_{i,j,k}$ | the binary variable equal to 1 if the fiber *(k)* on the link *(i, j)* is used to route at least one light-path, otherwise it remains 0 |

| | |
|---|---|
| $\delta_{i,j,k}^{s,d,w}$ | the binary variable equals to 1 if the wavelength *(w)* of the fiber *(k)* of the link *(i, j)* is used to assign a connection between the *(s)* and *(d)*, otherwise it remains 0 |
| $\delta_{i,j}$ | the binary variable equals to 1, if a link exists between the nodal pair *(i, j)*, otherwise it remains 0 |
| $\delta_{i,j,w}$ | the binary variable equals to 1, if a light-path is established between the nodal pair *(i, j)* using wavelength w; otherwise it remains 0. |
| $\delta_i$ | the binary variable equals to 1, if a node *i* is connected in the network topology; otherwise it remains 0 |
| $\delta_m$ | the binary variable equals to 1, if a node m is visited; otherwise it remains 0 |
| $\Lambda^{s,d}$ | traffic matrix |
| $\lambda_n$ | wavelength number *n* |
| $\lambda^{s,d}$ | the number of traffic requests from source *(s)* to destination *(d)*, $\lambda^{s,d} \in \Lambda^{s,d}$ |
| $\left(\lambda_{AOWC}^{s,d}\right)_W$ | the number of traffic requests satisfied by AOWC between *(s)* and *(d)* on *(w)* |
| $\left(\lambda_{NGR}^{s,d}\right)_W$ | the number of traffic requests satisfied without grooming and regeneration between *(s)* and *(d)* on *(w)* |
| $\left(\lambda_{pR}^{s,d}\right)_W$ | the number of traffic requests satisfied by 1R, 2R or 3R between *(s)* and *(d)* on *(w)*, where p ∈ [1, 2 and 3] is an integer, indicates type of the regenerator |

| | |
|---|---|
| $\left(\lambda_{TG}^{s,d}\right)_W$ | the number of traffic requests satisfied by TG, between *(s)* and *(d)* on *(w)* |
| 1R | Reamplification |
| 2R | Reamplification and reshaping |
| 3R | Reamplification, reshaping and retiming |