POWER BUDGET ANALYSIS FOR BROADCAST PASSIVE OPTICAL NETWORK

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A thesis submitted in fulfilment of the requirements for the award of the Degree Master of Engineering (Electrical)

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OCTOBER, 1999

DEDICATION

This research work is dedicated to my beloved father, Mr. LIEW SIN WAH for all his loving and caring throughout my life, my loving mother, Mdm Lim Gwi Peng and brother, Liew Foo Keong for their encouragement and love, my loving wife, Anika Zafiah binti Mohd Rus for her support and love.

ACKNOWLEDGEMENTS

Thank you ALLAH S.W.T for your blessing and guidance in completing this thesis. The author wishes to acknowledge all persons who have helped me during the period of research. Foremost the heartiest gratitude are due to my supervisor, Professor Dr. Mohd Nor bin Husain and Associate Prof. Dr. Mohd Zarar bin Mohd Jenu for their invaluable supervision, enthusiastic support and patient without which, this research would not have materialised.

The author also wishes to record his sincere appreciation to friends for their advice and moral support. Thanks also to the staff members of Electrical Department of Engineering, Institut Teknologi Tun Hussein Onn, especially the Microprocessor lab for their equipment support throughout this research.

Thanks to the participants of 1st East Asian Conference on Light-wave Systems, Laser and Opto-electronics (LISLO'99) and 1998 International Wireless and Telecommunications Symposium / Exhibition (IWTS'98) for their comment and advise. My appreciation to Encik Shobri Saad and Encik Zakaria Ali of MSC Projects Division, Telecom Malaysia Bhd for their information and comments towards my thesis.

Last but not least, the author is indebted to his parents and wife for giving the moral supports, guidance, advice and blessing.

PAPERS PUBLISHED ARISING FROM THIS WORK

1. Mohammad Faiz Liew Abdullah, Mohd Nor Husain, Mohd Zarar Mohd Jenu (1999) **" A Power Budget Analysis of FTTH Passive Optical Network".** 1st East Asian Conference on Lightwave Systems, Laser and Opto-Electronics (LISLO'99).

2. Mohammad Faiz Liew Abdullah, Mohd Nor Husain, Mohd Zarar Mohd Jenu (1998**) " A Basic Automatic System Design for FTTH".** 1998 International Wireless and Telecommunications Symposium / Exhibition (IWTS'98).

3. Mohammad Faiz Liew Abdullah, Mohd Nor Husain, Mohd Zarar Mohd Jenu (1997**) " Fiber To The Home (FTTH) – Potential And Reality ".** Journal Insititut Teknologi Tun Hussein Onn (Disember 1997, Vol. 1).

ABSTRACT

Optical fibre technology is vital for broadband communication and multimedia applications because single-mode optical fibres have a very low attenuation and a vast bandwidth at 1.3μm and 1.55μm wavelengths regions. The ever increasing demand for high speed data transmission and multimedia applications will inevitably results in optical fibre communication being used to replace copper cables all the way to the subscriber's home. A long term saving in maintenance cost can also be expected. This thesis presents an idealised mathematical model of the power requirement of a simple broadcast Fibre To The Home (FTTH) network based on the bus, star and bus-star topologies. Power requirement at central office (CO) is one of the main parameters that must be taken into consideration by system designers in their planning for the implementation of FTTH. A mathematical model was developed for each of the topology, which relates the power needed at the CO to the parameters of the network such as fibre loss, coupling loss, splitters loss, detection method and signal quality. This software package requires input specifications from the designer, and the output is a complete power budget analysis in a graphical form which can be used to understand the behaviour of each topology related to its power requirement. The numerical results show close agreement with manual power budget calculation using the same set of input parameters. The results can serve as useful guidance for system designers to evaluate the capability at the central office. However, apart from the limited topologies, the software concentrates mainly on one way transmission and limited modulation techniques. Future improvement can be implemented based on the software developed in this thesis.

ABSTRAK

Teknologi gentian optik merupakan satu teknologi yang penting dalam sistem perhubungan jalur luas dan penggunaan multimedia kerana gentian optik mod tunggal mempunyai kehilangan yang rendah dengan lebar jalur yang luas pada jarak gelombang 1.3μm dan 1.55μm. Permintaan yang tinggi untuk penghantaran data lebih cepat dan penggunaan multimedia akan mendorong gentian optik digunakan untuk menggantikan semua sambungan kabel kuprum hingga ke rumah pengguna. Dalam jangka masa panjang ia akan menjimatkan kos penyelenggaraannya. Tesis ini membentangkan satu model matematik keperluan kuasa penghantaran sehala sambungan gentian optik ke rumah mengenai rangkaian bus, rangkaian bintang dan rangkaian bintang-bus. Keperluan kuasa pada rangkaian pusat merupakan satu parameter utama yang perlu diambil kira oleh perekabentuk sistem dalam rancangan untuk mewujudkan sambungan gentian optik ke rumah. Satu model matematik telah dibangunkan untuk setiap rangkaian yang mengaitkan keperluan kuasa pada rangkaian pusat dengan parameter-parameter rangkaian seperti kehilangan gentian, kehilangan pembahagian, teknik-teknik pemodulatan dan kualiti isyarat. Perisian yang dibangunkan memerlukan spesifikasi data kemasukan daripada perekabentuk dan paparan keluarannya dapat digunakan untuk memahami ciri-ciri setiap topologi yang berhubungkait dengan keperluan kuasa. Keputusan pengiraan menggunakan perisian yang dibangunkan menunjukkan nilai yang hampir sama dengan pengiraan yang dibuat secara manual dengan menggunakan input parameter yang sama. Keputusan ini juga boleh membantu prekabentuk sistem dalam menilai keupayaan ibusawat pusat. Walaubagaimanapun, di samping daripada jenis rangkaian yang terhad, perisian yang dibangunkan hanya boleh membuat perkiraan keperluan kuasa untuk penghantaran sehala untuk beberapa jenis teknik pemodulatan. Namun demikian, perisian ini boleh dipertingkatkan lagi di masa akan datang berdasarkan perisian yang dibangunkan dalam kajian ini.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOL

A_c	-	Peak Amplitude of subcarrier
B	-	Bandwidth
B_a	-	Bandwidth of intensity modulated optical signal
B_M	-	Bandwidth of intensity modulated optical signal
B_T	-	Bitrate
c	-	Speed of light (3×10^8)
C_L	-	Total channel loss
D_f	-	Frequency Deviation Ratio
e	-	Charge of an electron
erfc	-	Complementary error function
F_n	-	Noise Figure
F(M)	-	Excess Avalanche Noise Factor
h	-	Planck's Constant (6.634×10^{34})
I_d	-	Dark current
I_p	-	Photocurrent
K	-	Coupling Factor or Boltzmann's constant
L	-	Distance in km
L_{cr}	-	Connector loss
L_e	-	Loss due to splitter in dB
L_j	-	Splicing loss
m	-	Number of connector
M	-	Avalanche Multiplication Factor
m_a	-	Modulation index
M_a	-	Safety Margin

n	-	Number of splicing
N	-	Number of subscribers
N_c	-	Number of couplers needed
P_a	-	Total power in baseband message signal
P_i	-	Power Required to transmit from central office
P_m	-	Total power in an intensity modulated optical signal
P_R	-	Power Received at tap node
P_S	-	Power Received at end user
R_L	-	Load Resistance
T	-	Absolute Temperature
Z_m	-	Average number of photons
α	-	Combination of fibre attenuation, Connector loss, Splicing loss
α_{fc}	-	Fibre attenuation
λ	-	Wavelength
η	-	Quantum Effciency
β	-	Splitter loss

LIST OF ABBREVIATIONS

ANSI	-	American National Standards Institute
BAP	-	Broadband Access Point
BER	-	Bit Error Rate
BIDS	-	Broadband Integrated Distributed Star
BISDN	-	Broadband Integrated Service Digital Network
BNR	-	Bell - Northern Research
BPON	-	Broadband Passive Optical Network
BT	-	British Telecom
CAC	-	Customer Accesses Connections
CAD	-	Computer Aided Design
CATV	-	Community Antenna Television
CCITT	-	Consultative Committee in International Telegraphy and Telephony
CO	-	Central Office (Exchange)
DTV	-	Digital TV
EDFA	-	Erbium Doped Fibre Amplifiers
EIA	-	Electronic Industries Association
EURESCOM	-	European Institute of Research and Strategic Studies in Telecommunication
FITL	-	Fibre in the Loop
FTP	-	File Transfer Protocol
FTTB	-	Fibre to the Basement
FTTC	-	Fibre to the Curb
FTTD	-	Fibre to the Desk

FTTF	- Fibre to the Floor
FTTH	- Fibre to the Home
FTTO	- Fibre to the Office
FTTS	- Fibre to the Street
FTTZ	- Fibre to the Zone
HDTV	- High- Definition Television
IEEE	- Institute of Electrical and Electronics Engineers
IMTV	- Interactive Multimedia TV
ISDN	- Integrated Service Digital Network
ITU	- International Telecommunication Union
LAN	- Local Area Network
LED	- Light Emitted Detector
NBS	- National Bureau of Standards
OAN	- Optical Access Network
ODN	- Optical Distribution Network
OLT	- Optical Line Terminal
ONU	- Optical Network Unit
PABX	- Private Automatic Branch Exchange
PCM	- Pulse Code Modulation
PON	- Passive Optical Network
POTS	- Plain Old Telephone Service
SCM	- Subcarrier Multiplexing
SNR	- Signal to Noise Ratio
SWAN	- Socio - cultural Welfare Advanced Network
TDM	- Time Division Multiplexing
TPON	- Telephony Passive Optical Network
WDM	- Wavelength Division Multiplexing

LIST OF APPENDIX

CHAPTER I

INTRODUCTION

1.1 General

The research of optical fibre as a transmission line started in the 1960s, where at the same time T.H. Maiman developed a ruby laser [1]. Initially, glass fibres having an attenuation of greater than 1000 dB/km were considered, but the systems were impractical. In 1966, K.C. Kao and B.A. Hockham at Standard Telecommunications Laboratories in England studied the loss mechanisms in fibres and anticipated a low-loss optical fibre along with the investigation of laser diode [2]. In 1970, when Kapron and his colleagues at Corning glass produced a fibre with a loss of 20 dB/km [3], optical transmission systems have become a reality, not a dream. The work towards reducing the fibre loss continued at several laboratories, and losses under 1 dB/km were obtained in pure silica fibres. Following the successful demonstration of a low-loss optical fibre, the first lightwave communication systems were developed using multimode fibres in combination with Light Emitting Diode (LED) or laser source. The big leap in performance of systems came with the development of a singlemode fibre, which has both lower dispersion and lower loss [4]. During the mid 1980s, coherent detection techniques were explored in optical fibre receiving systems [5]. Since then, fibre optic cable has been accepted as a viable communication medium. Today, communication transmission systems for trunk lines using optical fibres have been used worldwide.

In the past few decades, digital and optical communication technologies were evolving in such a rapid phase that a new integrated service in communication is needed. Based on Integrated Services Digital Network (ISDN), multimedia application and the introduction of fibre optic, Broadband Integrated Service Digital Network (BISDN) was proposed [6]. Initially, the system must be able to provide existing services for subscribers that is distributive TV (CATV), distribute Audio/ hi-fi, Telephony (POTS and ISDN) [7]. Broadcasting service will be one of the major services to be provided by BISDN where the digital video technology such as digital TV (DTV) and high definition TV (HDTV) have been widely accepted by major telecommunication companies for future deployment to subscribers [15]. Therefore, it is inevitable that fibre optic should be expanded to cover various user premises. This concept is known as Fibre in The Loop (FITL).

1.2 Background and Rational

In planning the FITL network, areas are to be divided into urban (corporate, high rise, shop houses, government office), suburban (industrial estate, shop houses, housing estate), rural (industrial estate, FELDA scheme, traditional village) and holiday resort. The various technologies and services to deploy a subscriber network that have been used are FTTO (Fibre To The Office), FTTC (Fibre To the Curb), FTTS (Fibre To The Street), FTTZ (Fibre To The Zone) and FTTH (Fibre To The Home). The future deployment however is dependent on geographical conditions, trends in policies and technological developments and existing networks. The layout for FTTO, FTTC, FTTS and FTTZ is to install optical cables to building entrances or unit areas of hundreds of subscribers where Plain Old Telephone Service (POTS) and CATV services are provided using copper lines and coax from the exchange (COT) to subscriber premises. The evolution of fibre in the local loop goes through the following stages, broadly categorised as :

i) Fibre to the office (FTTO)

This is equivalent to the direct feed cable in the present copper network. In this application fibre is terminated direct in the customer's premises, catering primarily to the demand of the corporate sector. FTTO comprises of :-

REFERENCE

1. Maiman, T. H (1960). " Stimulated Optical Radiation in Ruby Masers, " Nature. Vol. 187, 493.

2. Kao, K.C. and G. A. Hockham (1966) "Dielectric-Fibre Surface Waveguides for Optical Frequencies, " Proc. IEEE, Vol 113, 1151.

3. Hayashi, I., M. B. Panish, P.W. Foy, and A. Sumski. (1970) "Function Lasers Which Operate Continuously at Room Temperature, " Appl Phys. Lett., Vol. 17, 109.

4. Norio, Kashima. (1995) "Passive Optical Components for Optical Fibre Transmission. " Artech House, INC. 9.

5. Palais, J.C. and Bergstrom, C.S. (1992). "Digital Fibre Optic Network Synthesis." IEEE Lightwave Techonlogy, Feb, 27 – 33.

6. Gerhard Gobi, Carl Lundquist, Bernd Hillerich and Mark Perry. (1992) "Fibre to the Residential Customer." Journal Lightwave Technology, 165-169

7. Way, W.L. , Menendez, R.C. , Vogel T.R. , Cheung N.K. Wilson, D.S. (1988) " A new Method of Distributing Analogue CATV and POTS on fibre to the home." Journal Lightwave Technology, 1601- 1606

8. L.Coathup, J.P. Poirier, D. Poirier and D. Kahn. (1988). " Fibre to the home – Technology and Architecture Drives." IEEE Communications Magazine. 281 – 285.

9. Tom Rowbotham, Bill Ritchie and Cliff Hoppitt. (1989). " Plans for the Bishops Stortford (UK) fibre to the home trials." IEEE Communications Magazine. 1320 – 1325.

10. Camille Veyres and J.Jacques Mauro. (1988). " Fibre to the home : Biarritz (1984)…Twelve cities (1988)." IEEE Communications Magazine. 874 – 878.

11. B. Becker and M. Knucley. (1993). "Bandwidth Utilisation options for passive optical networks." EFOC & N'93, Fibre Optics Reprint Series, Vol 37 : Passive Optical Network. 270 – 273.

12. D.W Faulkner, P.J. Smith, C.A. Wade and J.R. Stern. (1993). " Evolution of PON systems." EFOC & N'93, Fibre Optics Reprint Series, Vol 37 : Passive Optical Network. 243-246.

13. G. Du Chaffaut, M. Borgne, S. Carpentier and J. Quive. (1992). "An attractive ATM PON proposal for FTTH connection." EFOC92, Fibre Optics Reprint Series, Vol 37 : Passive Optical Network. 192-195.

14. Yih-Kang and Maurice Lim. (1989). "New Architectures for Fibre Local Loop." Broadband'89, Fibre Optics Reprint Series, Vol 35 Number 1 : Fibre To The Home. 196-201

15. Robert, J. Hoss. (1990) "Fibre Optic Communications design Handbook." Englewood Cliffs, N.J. : Prentice-Hall. 372 – 376.

16. Telecom Malaysia. (1997) " Development section – Local Network. " July. " Tidak diterbitkan"

17. EURESCOM. (1998).," Full Services Access Network Requirements Specification." Project P614.

18. EURESCOM. (1998). " Implementation Strategies for Advanced Access Networks." Project 614, Deliverable 8, Elaboration of common FTTH guidelines.

19. EURESCOM. (1998). " Implementation Strategies for Advanced Access Networks." Project 614, Deliverable 11, Broadband Home Network for residential and small business.

20. Byeong Gi Lee, Minho Kang, Jonghee Lee. (1996). " Broadband Telecommunications Technology." 2nd .ed. Artech House.Inc.

21. Warren Hioki. (1998). " Telecommunications." 3rd . ed. Upper Saddle River, N.J. Prentice Hall. 1 - 9.

22. Uyless Black. (1993). " Computer Networks Protocols, Standards and Interfaces." 2nd. ed. Englewoods Cliffs, N.J, PTR Prentice Hall. 6 - 10.

23. Fred Halsall. (1996). " Data Communications, Computer Networks and Open Systems." 4 th. ed. Addison Wesley Publishing Company, 272 - 275.

24. John M Senior. (1992). " Optical Fibre Communications Principles and Practice." 2nd. ed. Prentice Hall. 638.

25. John R. Fox and Sam T.Jewell. (1990). " A Broad-Band distributed Star Network using Subcarrier Fibre Transmission." IEEE Journal on selected areas in communication, Vol 8 No.7 : Sep. 1223 – 1228.

26. A.R. Beaumont, I. R. Cade, P.D. Jenkins and D.B. Payne. (1988). " Passive Optical Multi-Access Networks for Telecommunications." IEEE Communications Magazine. 1 – 4.

27. Loria J. Baskerville. (1989). " Two fibres or One ? (A comparison of Two-fibre and One-fibre Star Architectures for Fibre to the home Applications)." Journal Lightwave Techonolgy, Vol 7 No. 11. 1733 – 1740.

28. Manseop Lee and Sungsoo Kang. (1994). " A FTTH network for Integrated services of CATV, POTS and ISDN in Korea." IEEE Communications Magazine, 261 – 263.

29. M. Zoboli and P.Bassi. (1989). " The number of Passive insertion in an Optical Fibre Data Bus." E-FOC 89, Fibre Optics Reprint Series, Vol 37: Passive Optical Networks, 1 – 6.

30. Mark Balmes, John Bourne and Jung Mar. (1990). " Fibre to the Home : The technology behind Heathrow." IEEE LCS, August. 25 – 29.

31. John Bourne, Mark Balmes and Jim Justice. (1990). " Heathrow – experience and evolution." IEEE Communications Magazine. 1091 – 1095.

32. Peter Keeble, Tim Finegan, Glenn Thomas, Anthony Cooper, Richard Grigsby, Chris Pegge and Philip Longhurst. (1991). " Optical Performance Specification and measurement of Local Loop Passive Optical Networks." Proceeding ICC' 91, 319 – 322.

33. C. Sierens, D. Mestdagh, G. Van der Plas, J. Vandewege, G. Depovere and P. Debie. (1991). " Subcarrier Multiple Access for Passive Optical Networks and Comparison to other Multiple Access Techniques." Proceeding Globecom 91. 619 –623.

34. Alberto Farina, Riccardo Rosi and Alberto Trondoli. (1992). " Fibre Loop Architecture : A Comparative Evaluation." Proceeding ICC '92. 1748 –1752.

35. Ozan K. Tonguz and Kenneth A. Falcone. (1993). " Fibre Optic Interconnection of Local Area Networks : Physical Limitations of Topologies." Journal Lightwave Technology, Vol 11. No. 5/6, May/June. 1040 – 1052.

36. D.D. Harman, G. Huang, G-H. Im, M-H. Nguyen, J-J. Werner and M.K. Wong. (1994). " Local Distribution for Interactive Multimedia TV to the Home." IEEE Communications Magazine. 175 – 182.

37. Gert Van der Plas, Raf Smets, Bruno Suard and Willem Verbiest. (1995). " Demonstration of an ATM- based Passive Optical Network in the FTTH trial on Bermuda." IEEE Communications Magazine. 988 – 992.

38. Ichiroh Sakakibara and Yutaka Motohashi. (1996). " Trial of CATV, VOD and ISDN services over FTTH." IEEE Communications Magazine. 33 – 38.

39. Anton H..H.Tan. (1997). " SUPER PON – A Fibre to the Home cable network for CATV and POTS/ISDn/VOD as economical as a coaxial cable network." Journal Light-wave Technology, Vol. 15. No.2, February. 213 – 218.

40. Tetsuya Miki. (1996). " Optical Access Networks Evolving toward Multimedia Information Environment." IEICE transactions on communications, Vol.E79-B, No.7, July. 885 – 889.

41. A.K.Agarwal, Raynet Corporation, Menlo Park. " Passive Fibre Optic Components for Subscriber Loop System ", Fibre Optics Reprint Series, Vol : 37 Passive Optical Network. 10.

42. Dalgoutte D G and Lea Wilson N D. (1995). " Installation cost issues in external plant." Annual Conference on European Fibre Optic Communication and Networks proceedings, 3, June.

43. Mellis J, Rabone N H, Redstall R M and Shaw R. (1994). " Performance and reliability requirements for passive components in local optical networks." 12th Annual Conference on European Fibre Optic Communications and Networks proceedings, 3, June.

44. Peacock J. (1994). " Measurements of optical transient attenuation losses and their effects on deployed optical systems in the British telecom network." Electronics Letters. 30, No 20. September.

45. Francix J, Peacock J, Cobb K and Bell P. (1995). " Investigations into the optical performance of a new generations of network plant items." 13^{th} annual Conference on European fibre Optic Communications and Networks proceedings, 3, June.

46. " A Splice for all seasons." GTE elastomeric splice test report, extracted from document #QR85-7700-001. (1985).

47. Results derived from PSI Lightlinker Burbank. CA. Fibre Optic Splice System data sheet. (1986).

48. Paul E. Green, JR. (1993) " Fibre Optic Networks." 1st.ed. Prentice-Hall International Editions. 355.

49. D.B. Payne, D.J. McCartney and P. Healey. (1982). " Fusion splicing of a 31.6km monomode optical fibre system." Electron. Lett. 18(2). 82-84.

50. David Brittain, Jon Sims Williams, Christopher McMahon. " A Genetic Algorithm Approach To Planning the Telecommunications Access Network."

51. Julia Case Bradley and Anita C. Millspaugh. (1999). " Programming in Visual Basic 6.0." 1st. ed. McGraw-Hill International Editions, Computer Science Series. 3 – 5.

52. Peter Spasov. (1999). " Programming for Technology Students using Visual Basic." 1st. ed. Prentice Hall, Inc. 16 – 17.

53. Diana Zak. (1999). " Programming with Microsoft Visual Basic 6.0." 1st.ed. Course Technology. 5.

54. David I. Scheider. (1998). " An Introduction to Programming using Visual Basic 5.0." 3rd. ed. Prentice Hall, Inc. 23 – 24.

55. Arnab Sarkar. " Fibre Design Considerations for Optical Telecommunication. " Light-wave Technologies, Inc. 67.

56. Jasprit Singh. (1995) " Semiconductors Optoelectronics – Physics and Technology." 1st. ed. McGraw-Hill International Editions. 652 – 653.

57. John Powers. (1999) " An Introduction To Fiber Optic Systems." 2nd. ed. McGraw-Hill International Editions. 37.

58. K.Furuya and Y.Suematsu. (1980) " Random-Bend Loss in Single-Mode Fibers and Parabolic-Index Multimode Optical Fiber Cables." Appl. Opt. Vol. 19, No. 9. 1493 – 1500.

59. L. B. Jeunhomme. (1983) " Single-mode Fiber Optics." New York : Marcel Dekker.

60. F.P.Kapron. (1985) " Fiber Optics System Trade-offs." IEEE Spectrum. 68 – 75.

61. J. Straus and B. Kawasaki. " Optical Fiber Transmission - Passive Optical Components." Howard W. Sams and Co, Macmillan. 241.

62. C.A. Brackett. (1992) " A perspective on scalability and modularity in multi-wavelength optical networks." Workshop on WDM Technologies, Systems and Network Applications, Optical Fibre Communications Conference.

63. H. Paul and J. Tindle. (1996) " Passive Optical Network planning in Local Access Network." BT Technology Journal, 14, 2. 110 – 115.

64. R. E. Wagner and R.A. Linke (1990). " Heterodyne lightwave systems: Moving towards commercial use." IEEE Magazine, Lightwave Communication System. 28 – 35.

65. P. E. Green and R. Ramaswami (1990). " Direct detection lightwave systems: Why pay more?." IEEE Magazine, Lightwave Communication System. 36 - 49.

66. EURESCOM. (1996)., " Access Network Evolution and preparation for Implementation. " Project P306, Deliverable 3, Strategic Recommendations for FITL Systems.

67. Louboutin and Legros Rochefort. (1988). " Powering of Subscriber's Optical Network Terminals on FTTH and FTTC Networks." IEEE Spectrum.

68. Corning Glass (1989). " Response to NTIA Request for comments on the Competitiveness of the U.S Telecommunication Industry. "

69. Paul W. Shumate Jr (1989). " Optical Fibres reach into homes." IEEE Spectrum.

70. Lester D. Taylor (1988). " On the Measurement of Marginal Costs. " University of Arizona.