Cost Effective ROF Communication System for CATV Channels over WDM Network and Fuzzy Modeling of the System

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***Abstract*— A radio over fiber (RoF) communication system is considered for cable television (CATV) channels over wavelength division multiplexing (WDM) network using an optical direct modulator (DM). Since the DM bandwidth is limited, increasing bandwidth efficiency of the system using M-ary quadrature amplitude modulation (MQAM) schemes will improve the link symbol error rate (SER) performance. Radio frequency (RF) signals with constellations of 16-64-256 QAM were simulated for CATV channels and the effect of using higher bit per symbol on the link performance was studied in order to reduce the cost of the network through utilizing financially feasible optical modulator. The 64-QAM scheme which is the most appropriate is used for the system of CATV channels. The link performance is studied for different combinations of effective parameters such as AC electrical power and Module to Bias ratio, which are crucial to be set properly, and SER is obtained at the front end of the receiver. The best setting options are proposed for 30 CATV channels with 64-QAM constellation with direct modulation transmitted over the 4-WDM link. Moreover, communication system is modeled by fuzzy logic using data-base obtained from simulation. Fuzzy reverse modeling of the system is also implemented in order to provide reasonable estimate of electrical power required to achieve a desired SER. Characteristics of forward and reverse fuzzy modeling are discussed. Simulation results represent satisfactory performance of the models.**

***Index Terms*— Direct Modulator (DM), Fuzzy Logic, Fuzzy Reverse Modeling, Radio over Fiber (ROF)**

I. Introduction

For accommodating with the increasing demand of transmitting multiple data channels simultaneously through a fiber link, efficient and economic network design is valuable. Different optical modulation methods can be used for transferring CATV signals from electrical domain to the optical [1]. Only some modulation methods are cost-effective and reliable. We have considered various electrical M-QAM schemes for transmitting 30 CATV channels over a 4-WDM RoF network. The cost effective optical modulation method for a WDM network with four or less routes is utilization of DM for each route [2]. However, bandwidth of RF signals, laser clipping, chirping and nonlinearity effects can limit the quality of the link performance [3]. Using DM laser is cheaper than using the external modulator. But in return, a DM laser with a higher bandwidth will be needed to support the RF signal spectra. The higher the bandwidth of the DM laser, the higher the cost. On the other hand, increasing the number of bits per symbol will decrease the required laser bandwidth and will consequently reduce the cost; higher M-QAM brings more SER in the symbol detection stage. Hence, there should be a tradeoff between using laser with higher bandwidth and utilizing higher M-QAM scheme in order to achieve the optimum link SER while reducing cost of the network. Furthermore, different system adjustments in order to achieve a linear performance of the direct modulator laser are important for analog transmission of RF signals [4]. Some parameters such as electrical power of the RF signals and DM laser characteristic parameters may result in linear or non-linear behavior of the DM laser. Also, an appropriate laser biasing prevents undesirable effects of the laser clipping, nonlinearity, and affects the modulator bandwidth based on the rate equation modeling [4]. Fuzzy modeling uses the actual input output data of the system to imitate its behavior [5], while, Fuzzy reverse modeling deals with outputs of the system or a mixture of some inputs with the outputs of the system in order to estimate the required values of other remaining inputs.

II. Overcoming the DM Laser Limitations through Optimized System Design

For increasing the efficiency of a system's bandwidth, using higher number of bits per symbol can be a solution. Bandwidth efficiency is defined as follows [6]:

$$\frac{R}{W}=\frac{K}{WT_s}=\frac{1}{WT_b}\ bits/s/Hz \quad ; \quad K=\log_2 M \qquad (1)$$

Where R is the bit rate, W is the bandwidth, T_s, T_b, K and M represent symbol duration, bit duration and number of bits per symbol and symbol alphabet size, respectively. Drawback of increasing K is the increase in bit error rate which in case of

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M-QAM signals up to some level is not as noticeable as the other M-ary schemes and is represented as follows [6]:

$$P_B \approx \frac{2(1-L^{-1})}{\log_2 L} Q\left[\sqrt{\left(\frac{3\log_2 L}{L^2-1}\right)\frac{2E_b}{N_0}}\right] \quad ; \quad L = \sqrt{M} \qquad (2)$$

P_B is QAM probability of bit error and Q(x) is complementary error function. Consequently, there is a limit for increasing the bandwidth efficiency due to the rise in detection error probability. The other factor is laser chirping which increases SER significantly and can be introduced by the frequency change $\Delta f(t)$ [4]:

$$\Delta f(t) \approx \frac{\alpha}{4\pi}\frac{d}{dt}\ln P_{out}(t) \qquad (3)$$

Where, α and $P_{out}(t)$ are chirping factor and optical output power respectively. $\Delta f(t)$ is the frequency excursion of the output light. Increasing the bias level of the laser will result in lower laser chirping ($P_{out}(t)$ will not change rapidly) but will impose higher power penalty due to lower extinction ratio of the laser [7]. Therefore, there should also be a tradeoff between decreasing laser chirping and avoiding large power penalty. Furthermore, lowering the changing rate of $P_{out}(t)$ will reduce the chirping effect.

There is a limit on the bit rate of the data which is modulated by the DM laser. Modulation bandwidth of the DM laser based on the derivation from the rate equations is proportional to the biasing current [4]:

$$\mathrm{BW} \approx \sqrt{\mathrm{I_B} - \mathrm{I_{TH}}} \qquad (4)$$

Where BW represents the DM laser bandwidth, $\mathrm{I_B}$ and $\mathrm{I_{TH}}$ are biasing and threshold currents respectively. Increasing $\mathrm{I_B}$ as much as possible beyond the $\mathrm{I_{TH}}$ can increase the modulation bandwidth. However, the increase in biasing current has drawbacks and there should be a compromise.

III. System Analysis

Fig. 1 shows the system structure which is simulated in VPI software package.

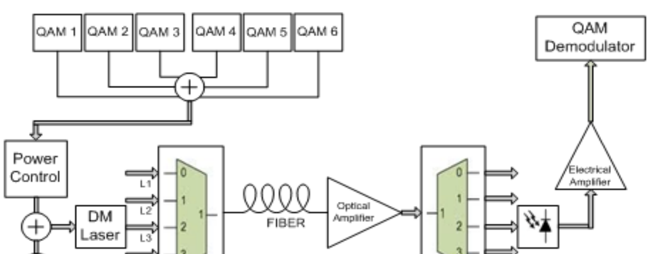


Fig. 1. System of RoF multiplexed on 4-WDM

This system includes four different wavelength-routes with channel spacing of 100 GHz. Each route contains six QAM blocks each of which has five M-QAM channles with bit rate of 30 (Mb/s) for every channel, resulting in total bit rate of 900 (Mb/s) optically modulated on each wavelength-route. It should be noted that the simulation results will be approximately in the same range for different combinations of number of M-QAM channels with practical CATV data rate per channel as long as the total bit rate sums to 900 (Mb/s) for each wavelength-route. For representation purposes of this article, only the results for one of the four routes, i.e. route No 2 as represented in fig. 1, is presented. At the Power Control block, the electrical power of the 30 CATV channels will be set in order to sweep different power values in dBm to give the simulation results of the electrical power effect on the link performance by observing the SER at the front end of the QAM demodulator block. RF signals are then superimposed on a fixed DC bias current to intensity modulate the optical carrier [8]. The next block is optical direct modulator which is simulated based on numerical solutions of the single-mode rate equations. This block can show the nearly single-mode Fabry-Perot (FP) laser and can be modeled in more details by the laser equations in normalized form as follows [9]:

$$\frac{dE}{dt} = \frac{1}{2\tau_{ph}}\left[\tilde{G}(N,|E|^2)|E|^2 - 1\right]E + F_E(t) \qquad (5)$$

$$\frac{dN}{dt} = \frac{1}{\tau_e}\left[\frac{J_{bias}+J_{mod}(t)}{J_{th}} - N - G(N,|E|^2)|E|^2\right] + F_N(t) \qquad (6)$$

Where, N and $\tilde{G}$ are normalized carrier density and laser gain to their values at the laser threshold, respectively. J_{bias}, J_{mod}, J_{th} and E, are the laser bias, modulation, threshold currents and the electric field, respectively. τ_{ph} and τ_e are the photon lifetime and the carrier lifetime respectively.

A 4-WDM is used for multiplexing 4 routes and RF signals are routed on a single mode fiber and then are being optically amplified. At the end point of the system, after the de-multiplexer and the electrical amplifier an M-QAM detector is utilized in order to study performance of one of the channel frequencies.

IV. Simulation Results

For transmitting 30 QAM CATV channels with bit rate of 30 (Mbits/sec) per channel over 40 (km) single mode fiber a set of NTSC-M standard carrier frequencies (301.25 MHz-475.25 MHz) are selected. At the receiver side, one of the CATV channels with 397.25 (MHz) is studied. Since, for analog signal transmission through fiber the 1550 - 1555 nm wavelength range is the optimum range [10], laser center wavelength is set to 1553 nm. Moreover, according to the equation (6), increasing (J_{bias}/J_{th}) and ($J_{mod}(t)/J_{th}$) will affect the DM laser performance. In the VPI model of DM laser two coefficients can be set as(J_{bias}/J_{th}), (J_{mod}/J_{th}). If we define a new ratio of these two coefficients ($m = J_{mod}/J_{bias}$) called Module-Bias ratio, by fixing (J_{mod}/J_{th}) = 1, and changing the (J_{bias}/J_{th}) the optical output power will change due to different values of “m”. The actual ac electrical power in the system is influenced by both the ratio (J_{mod}/J_{th}) and the ac power value being swept in the power control block. Therefore, for simplicity of simulation, we manually set the ratio (J_{mod}/J_{th}) to 1 so that there remains only one variable - i.e. the ac power value determined by power control block - to study as the ac electrical power. The smaller the “m” the larger the laser biasing level. Appropriate adjustments of this ratio “m” and AC electrical power of the RF signals have a vital role in obtaining an acceptable SER for the transmission of M-QAM CATV channels over the fiber. Fig. 2 shows the SER performance of the system when applying different sizes of M-ary QAM modulation for different values of "m" with the ac electrical power is fixed at -5 dBm. From the figure it can be inferred that 64-QAM modulation will result in the least SER for all values of "m". This shows that for k=6, tradeoff between more bandwidth efficiency and less symbol detection error is well set for 64-QAM. The 16-QAM ends up not to a large enough bandwidth efficiency and therefore will have worse SER compared to 64-QAM due to the bandwidth limitation of the DM laser. Although, 256-QAM has the largest bandwidth efficiency, it results in an unacceptable SER due to larger symbol alphabet size and closer received symbol detection threshold compared to that of 64-QAM.

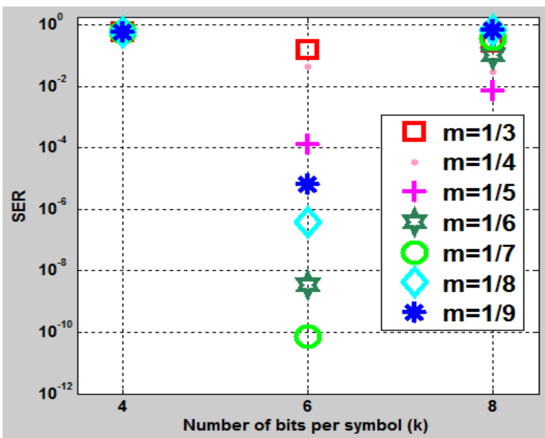


Fig. 2. SER for 2^K-QAM channels vs. K; ac electrical power at -5dBm

In Fig. 2 the values of SER in case of K=6 is enhanced through decreasing "m" up to m=1/7 and then for m<1/7 it is degraded. This shows according to equation (4) and (3) that increasing (J_{bias}/J_{th}) up to some level will add the modulation bandwidth of the DM laser and will reduce chirping effect. However, for (J_{bias}/J_{th}) >7, the DM performance will be degraded due to either nonlinearity or extinction ratio power penalty.

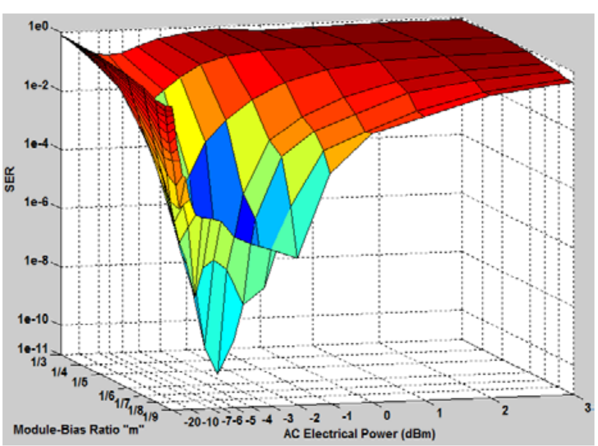
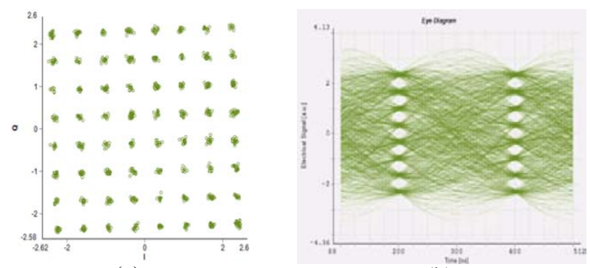


Fig. 3. SER vs. "m" and ac electrical power for received 64-QAM channel with carrier frequency= 397.25 (MHz)

Electrical power of the RF signals is being controlled by power control module as shown in fig. 1 and is swept from -20 dBm to 3 dBm. The 3 dimensional diagram of 64-QAM CATV channels SER performance for different values of AC electrical power and different values of "m" is represented in fig. 3.

Fig. 3 shows that increasing signal electrical power up to some level will result in better Signal to Noise Ratio (SNR) and therefore lowers the SER. However, after some threshold nonlinearity due to higher power level degrades the SER performance of the link. There should be a tradeoff between higher signal to noise ratio (SNR) and lower nonlinearity for the system.

According to fig. 3, proper adjustments of ac electrical power and "m" will guaranty an acceptable SER (up to 7.05E-11 for ac power=-5 dBm and m=1/7) for the transmission of 64-QAM CATV channels over fiber. Fig. 4 shows the constellation diagram and the corresponding eye diagram of the received 64-QAM channel (carrier frequency= 397.25 (MHz)) with SER=7.05E-11.



(a) (b)

Fig. 4. Received and detected signal for 64-QAM channel with carrier frequency= 397.25 (MHz); (a) Constellation (b) Eye Diagram

V. Fuzzy Modeling

Fuzzy logic [11] is used for modeling of the communication system. Two input variables to the fuzzy inference system (FIS) are electrical power, i.e. P (dBm), and module-bias ratio, i.e. "m". Rules of the inference engine are determined based on human reasoning so that the FIS will be able to replace the communication system itself. Output of the fuzzy model will be the estimated value of symbol error rate (SER) which is supposed to be the same as that of the actual system. As represented in Equation 7, ratio of absolute difference between output of the fuzzy model, i.e. $\hat{X}$, and that of the actual communication system, i.e. X, to the actual system output determines the error, e ,which has to be reduced in order for the fuzzy model to estimate the actual system precisely:

$$e = \frac{1}{p \times r} \sum_{i=1}^{p} \sum_{j=1}^{r} w_{ij} \frac{|X_{ij} - \hat{X}_{ij}|}{X_{ij}} \qquad (7)$$

where p and r represent the number different electrical power and number of different module-bias ratio settings used for modeling respectively, and w_{ij} is the weight factor used to emphasize the importance or sensitivity of some settings compared to the others. Using w_{ij} it is possible to eliminate regions which are of lower interest for communication purposes such as points where higher electrical power are required or areas that the setting of module-bias ratio is typically not feasible for communication system settings, e.g. extremely low values or values higher than $\frac{1}{4}$.

Simulation results of the communication system for electrical power setting between -20 dBm to 3 dBm, with step size of 1 dBm, and module-bias ratio setting from $\frac{1}{9}$ to $\frac{1}{3}$ were obtained using VPI simulation tool and were used for the purpose of fuzzy modeling; In other words, p and r are 24 and 7 respectively. Region of interest for this case study includes results obtained for electrical power between -12 dBm and -2 dBm, and module-bias ratio between $\frac{1}{8}$ and $\frac{1}{5}$ for which the average value of relative error is computed using equation 6 and its reciprocal is regarded as the fitness function for smart search in genetic algorithm.

Two sample rules of the fuzzy inference engine are as follows:

-- IF the *Module-Bias ratio* is ***Very Low***, **AND** the *Electrical Power* is ***Very Low***, **THEN** the *SER* will be ***Medium***.

-- IF the *Module-Bias ratio* is ***Low***, **AND** the *Electrical Power* is ***Medium***, **THEN** the *SER* will be ***Very Good***.

where the medium value for SER could be for example around 10^{-5} while SER values in the range 10^{-9} are considered very good depending on the application requirements and structure of the system.

A total of 25 rules are defined for the fuzzy model with 5 membership functions for each input variable, and five membership functions for the output variable.

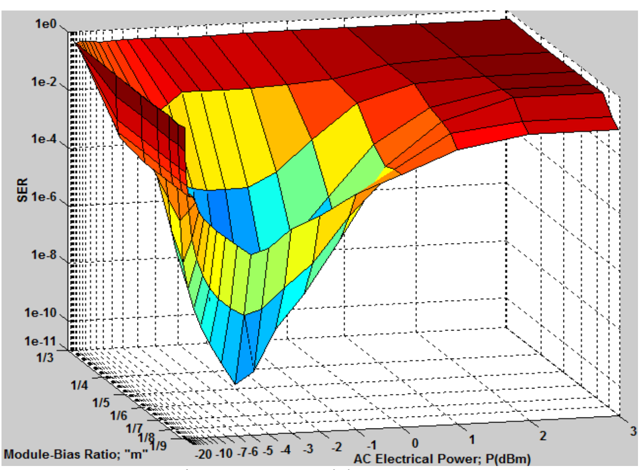


Fig. 5. Fuzzy Model output; SER

Fig. 5 represents the 3D diagram of two inputs versus one output of suboptimal fuzzy model obtained by the genetic algorithm search method using 150 generations with population of 200 per generation while each offspring had 3 chromosomes, corresponding to three variables mentioned before, each of which included 15 cells for all the edges and centers of fuzzy sets of the appropriate variable. The average value of error, see equation 6, is reduced below the required limit in regions of interest obtained by the fuzzy model.

Fig. 6 represents the actual error between the fuzzy model output and the simulated system using VPI software. The values represented in fig. 6 are the difference between the values of SER represented in fig. 3 and fig. 5 for all the points in the two diagrams.

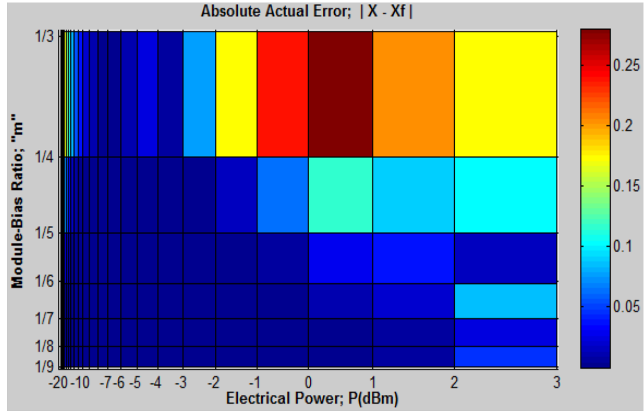


Fig. 6. Actual absolute error between the estimated SER and the actual SER

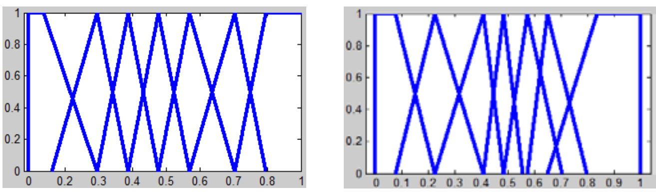
From fig. 6 it is inferred that the fuzzy model has satisfactory performance since the maximum relative error of estimated SER is low enough. Also, the average relative estimation error is 3.9 within the region of interest. This means $\hat{X}$ is between $X/3.9$ and $3.9X$ where $\hat{X}$ and X are the estimated SER and the actual SER respectively. This is a precise estimation for values as small as SER=7.05×10^{-11}.

VI. Fuzzy Reverse Modeling

In fuzzy reverse modeling, the processes of fuzzification, defuzzification, inference, feeding the inputs and getting the output is the same as fuzzy modeling. The major difference is that in this scenario the fuzzy reverse model is fed by Module-Bias ratio and SER, and the output of the reverse model will be the estimated electrical power. As mentioned before, the Module-Bias ratio was one of the inputs to the fuzzy model along with electrical power, and the output of the fuzzy model was SER. In reverse scenario, one of the inputs, here Module-Bias ratio, along with the output of the actual system, here SER, will be fed to the reversed inference engine in order for the required value of the other input, in this case the electrical power, to be estimated. This can be helpful specifically when the system model is significantly large and sophisticated and a relatively huge amount of time and effort is required to adjust the variables and feed the inputs to the system and run time-consuming simulations repeatedly in order to be able to find the set of inputs which provide the user with some desired SER. In such cases, one smart way can be to run a limited number of simulations, record the data and form the fuzzy reverse model. The input adjustments for the training process should be suitably chosen in order to cover the whole area of interest so that the reverse system can be mimicked accurately. After the fuzzy reverse model is formed, the next step is to simply feed the Module-Bias ratio being used for the system and the desired SER to the reverse model. The output will be an estimate of the lowest amount of electrical power required to achieve the desired performance for the adjusted value of Module-Bias ratio. Also, based on the data set obtained by the communication system, an accurate fuzzy reverse model can represent if the desired SER is not achievable for some setting of Module-Bias ratio due to non-linearity of the link.

A total of 35 rules are defined for the fuzzy reverse model with 5 membership functions for Module-Bias ratio, 7 membership functions for SER. Output variable of the fuzzy reverse model, i.e. the estimate of the required electrical power, also had 7 membership functions in this model.

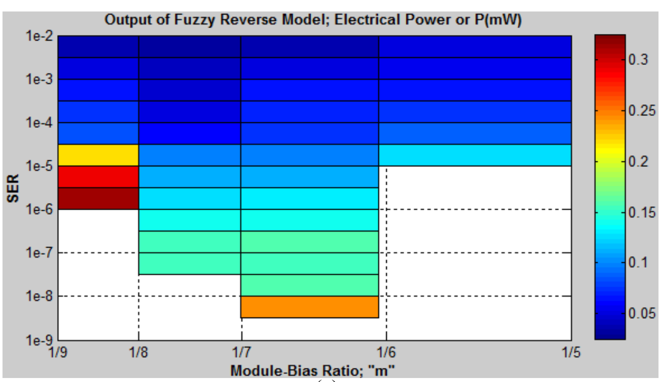
Genetic algorithm was deployed on top of the fuzzy reverse model with the same adjustments mentioned for fuzzy modeling while in this case each chromosome of the input variable SER and also each chromosome of the output variable electrical power had 21 cells since these two variables had 7 membership functions which result in 21 edges for each.



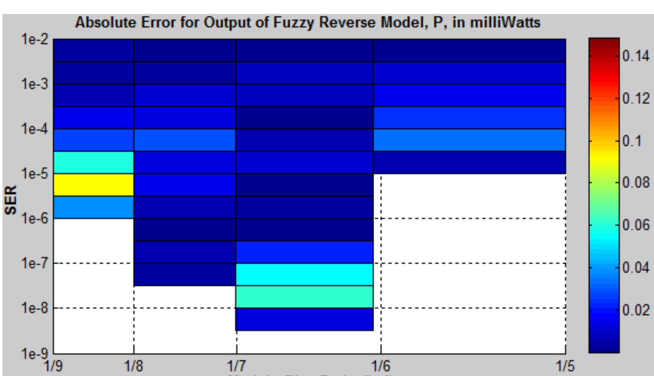
(a) (b)

Fig. 7. Suboptimal fuzzy sets obtained by genetic algorithms for fuzzy reverse model; (a) Input variable; SER (b) Output variable; power

Fig. 7 represents the normalized final fuzzy sets obtained by the genetics algorithm for the input variable SER and the output variable, i.e. electrical power.



(a)



(b)

Fig. 8. Fuzzy reverse model results;
(a) Output, estimated electrical power (mW)
(b) Absolute error for electrical power estimation (mW)

Two-dimensional view for the simulation results including the output of the fuzzy reverse model and the error associated with estimation of the required electrical power are represented in fig. 8a and fig. 8b respectively.

Fig. 8b represents the absolute value of the actual error for electrical power estimation using fuzzy reverse model in milliWatts. Within the region of interest, the estimation error is far less than 0.02 mW in almost a 2 mW range for ac electrical power, which means error percentage or the estimation tolerance is less than 1%. This implies that the fuzzy reverse model has a satisfactory performance within the region of interest. This must also be noted that in fig. 8a, the points where no power estimation is made show actually the adjustments for which the desired SER could not be achieved at all regardless of how much electrical power was available.

VII. Conclusion

For transmitting CATV channels over a 4-WDM optical fiber communication system utilizing the DM laser is the cost effective design. DM laser bandwidth limitation can be overcome by increasing bandwidth efficiency. 16-QAM scheme will not increase bandwidth efficiency enough while 256-QAM exhibits an unacceptable SER due to its large symbol alphabet size and closer detection thresholds. 64-QAM scheme will result in an acceptable SER for transmitting 30 CATV channels with bit rate of 30 (Mb/s) per channel when an optimized adjustment of RF electrical power and laser biasing is considered. A proper selection of electrical power and Module-Bias ratio can control DM laser nonlinearity and chirping effect. System was modeled using fuzzy logic which helps obtain results for a continuous range of inputs. Fuzzy reverse modeling was also implemented on the system in order to estimate the value of electrical power required to achieve the desired SER for different settings of Module-Bias ratio. Both fuzzy model and fuzzy reverse model had satisfactory performances and speed with relatively low complexity.

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