Rafał KRÓLIKOWSKI

Politechnika Wrocławska, Instytut Telekomunikacji, Teleinformatyki i Akustyki

HFC network return path performance modeling

***Abstract**. The paper presents a complete model of a HFC cable TV return path, which allows for calculation of ratio of carrier to cumulative noise and interference at important points of network. Return path transmissions are carried out using multiple M-QAM carriers. The model was verified using real-life measurements and a variety of simulations allowed for assessment, which return path parameters have the highest influence onto performance, as well as, the parameter values, which allow for the highest data capacity. (**Modelowanie wydajności kanału zwrotnego w sieciach HFC**).*

***Streszczenie.** W artykule przedstawiono kompletny model toru zwrotnego sieci telewizji kablowej budowanej w technologii hybrydowej HFC, pozwalający obliczyć odstęp nośnej od skumulowanych szumów i zakłóceń w istotnych punktach sieci. Transmisja w torze zwrotnym odbywa się z wieloma podnośnymi M-QAM. Model poddano weryfikacji pomiarowej. Przeprowadzono szereg badań symulacyjnych mających na celu pokazanie, które parametry toru zwrotnego mają największy wpływ na jego pracę oraz jakie wartości tych parametrów maksymalizują jego pojemność informacyjną ograniczoną poziomem szumów i zakłóceń.*

Keywords: hybrid CATV networks, return path transmission, performance modeling
Słowa kluczowe: hybrydowe sieci TVK, transmisja w torze zwrotnym, modelowanie wydajności sieci

Introduction

Modern cable TV systems apply HFC (*Hybrid Fiber Coax)* (fig.1) technology, where the coaxial network segments have a hierarchical (tree) topology and where the coax subscriber links branch out from the *ONU* (*Optical Network Unit*) nodes. As for ONU nodes, these are connected through a star optical network to the network's headend. Besides standard broadcast TV and radio, cable TV networks also provide an increasing number of various two-way services using the return path (uplink), such as: Internet access, e-mail, voice/telephone services or video on demand. Considering the increasing use of return path digital transmissions it is important to be able to model the return path and relate its data capacity to the network topology. This paper presents such a model along with a variety of simulation results, aimed at identifying the key parameters affecting return path performance.

One of the main problems when designing new HFC cable TV networks or planning modernization of old ones is to properly size the coax network segment for each ONU node. Deep network segmentation, i.e. major reduction of subscriber sockets per each optical node, for example 100 per node, obviously would be advantageous to the subscriber in regards to the available bandwidth.

However, the costs arising from the need to expand the optical network as well as the maintenance/functional aspects, such as for example the much more difficult fiber optic workmanship compared to coax, seem to justify having a larger coaxial network segment. This is especially true for existing cable TV networks, where one would prefer to maintain as much as possible of the existing network infrastructure.

Downlink modeling is possible using a variety of cable network design software. It covers the classical model of coaxial links with a cascade of amplifiers, with the addition of optical links. This model can also be successfully applied for analysis of digital channel downlinks using M-QAM modulation, as 64-QAM and 256-QAM has lower requirements pertaining to CINR (*Carrier to Noise and Interference Ratio*) as compared to analog AM-VSB TV transmissions. The only requirement here is to check the influence of the increased number of channels onto the intermodulation parameters. The situation is quite different when it comes to the return path uplink. Here the interferences can cumulate from the individual coax branches and we also experience interference source dispersion related to the direction of transmission. This causes a high level of noise and interference at the input of the ONU node as compared to the downlink.

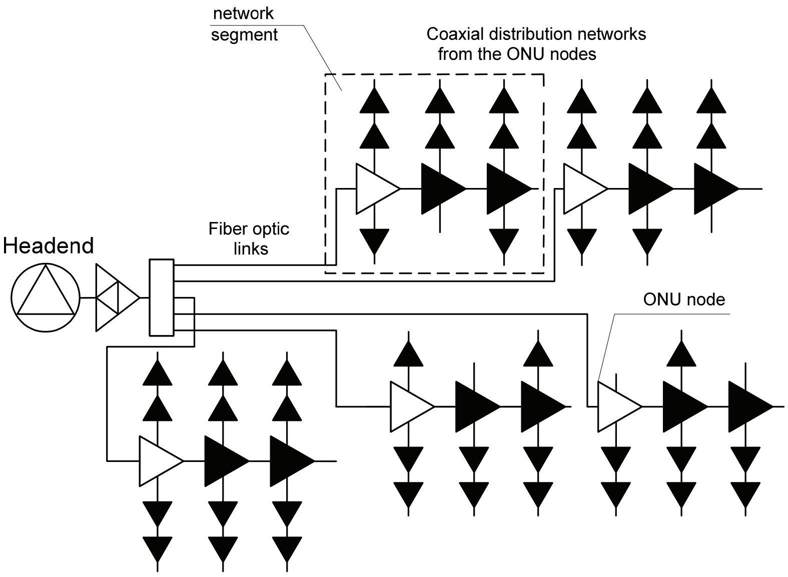

Fig. 1 Hybrid Fiber Coax (HFC) network structure

Another consideration is that the uplink bandwidth should be less than 10% of the downlink bandwidth. Considering that the downlink bandwidth is almost 13 times larger than the return path, it is the return path, which is the major bottleneck of cable TV systems.

This paper proposes a return path model, which can be applied for design of active return path HFC (*Hybrid Fiber Coax*) networks. This model was successfully verified through actual measurements at several cable TV networks throughout Poland. It allows for a variety of analyses, which in turn allow for optimization of the cable network design. The problem of efficient return path transmissions was presented in many publications [1], [2], [3], [4], however, so far we haven't seen any complete return path model, which would link the network parameters and topology to its transmission parameters, thus allowing for assessment at the design stage of proper system operation.

Modeling of the return path information capacity

Return path information capacity depends on the available transmission band, which in European countries (including Poland) is defined within 5 MHz to 65 MHz (5 MHz to 42 MHz for USA) [5], along with the carrier to noise and interference ratio (CINR) at the demodulator input. Whilst the available band is fixed and cannot be changed by us, we can vary the number of transmission channels and thus increase the throughput of the return path. We can also change the CINR by adjusting the network parameters and topology to match the transmission requirements. As we shall show, the key things affecting the dynamic range of the return path are:

a) For the optical part of the HFC network – proper matching of the optical transmitter power to the attenuation characteristics of the link as well as selection of operating parameters of the optical transmitter, depending on the number of transmitted return channels [1], [7],

b) For the coax part of the HFC network – proper selection of the number of subscriber sockets leading to a single ONU node, depending on the number of transmitted return channels, subscriber distribution and return path amplifier settings [8].

Optical part of the HFC network

Assuming independence of the optical and coax network noise and interference sources, we can define the total incidental carrier to noise and interference ratio in the return path $CINR_{TZ}$ based on the relation:

$$CINR_{TZ} = -10\log\left(10^{-\left(\frac{CINR_{ONU}}{10}\right)} + 10^{-\left(\frac{CINR_{LINK}}{10}\right)}\right) \tag{1}$$

where: $CINR_{ONU}$ is the carrier to noise and interference ratio at the input of the return path optical transmitter, $CINR_{LINK}$ is the carrier to noise and interference ratio of the optical link. Optical return links are usually short point-to-point connections. We don't use passive division of optical power as in the broadcast channels. On the other hand, it can and often does include wave multiplexing, which implies additional attenuation of the optical path, due to multiplexer and demultiplexer losses. Optical link noise comprises of transmitter noise (*RIN – Relative Intensity Noise*) and receiver noise (shot noise and thermal noise). One can compensate for the thermal and shot noise of the optical receiver, by appropriately increasing the optical transmitter output power, i.e. proportionally to the attenuation of the optical link (please see fig. 2).

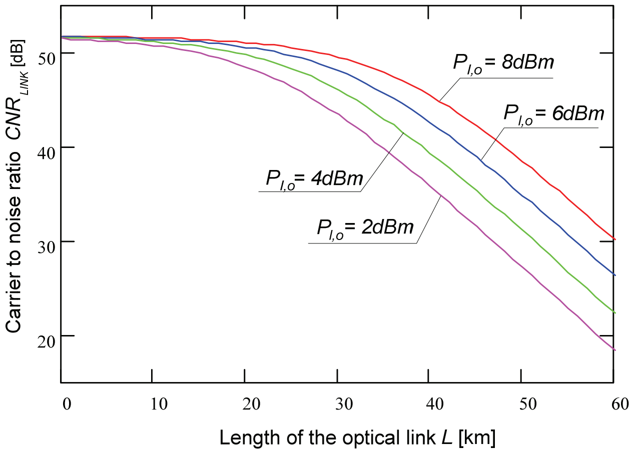

Fig.2 Carrier to noise ratio CNR_{LINK} as function of the optical link length L for different transmitter power levels $P_{l,o}$

For an optical link with dominant *Relative Intensity Noise* the $CINR_{LINK}$ can be defined using relations [1]:

$$CINR_{LINK} = -10\log\left(10^{-\left(\frac{CNR_{RIN}}{10}\right)} + 10^{-\left(\frac{CNLD}{10}\right)}\right) = \tag{2}$$

$$= -10\log\left[10^{-\left(\frac{-RIN - 10\log(B_N) + 20\log\left(\frac{\mu}{\sqrt{N}}\right)}{10}\right)} + 10^{-\left(\frac{\frac{1}{2}\sqrt{\frac{\pi}{2}}\mu^{-3}\left(1+6\mu^2\right)e^{1/2\mu^2}}{10}\right)}\right]$$

where: CNR_{RIN} - carrier to RIN ratio, $CNLD$ - carrier to non-linear distortion ratio (caused by transmitter signal clipping), RIN - spectral noise density of the optical transmitter, B_N - bandwidth of a single return channel, N - number of return channels in return path,μ - RMS value of the optical modulation index for a multichannel signal, ($\mu = \sqrt{N} \cdot m_{rms}$, m_{rms} – optical modulation index of a single channel).

Applying the relation (2) we have plotted the carrier to noise ratio of the optical link $CINR_{LINK}$ as function of RMS of the modulation index for each return channel m_{rms} and for different received power levels $P_{o,d}$ (fig.3), as well as for a different number of return channels (fig.4).

Based on the presented relation (2) and figures 3 and 4 we can formulate the general conclusions pertaining to direct modulation and detection optical return links, which are commonly used to provide return channels:

1) The plot of the $CINR_{LINK}(m_{rms})$ function has two slopes:

a) a rising slope, starting at low m_{rms} values, relates to the increasing carrier to noise ratio of the optical link as the optical transmitter output signal level increases, which in turn means an increase of the optical modulation index. Here, the m_{rms} $CINR_{LINK}$ value increases linearly with the increase of the RF signal at the optical transmitters input. With the further decrease of the received optical power $P_{o,d}$ (e.g. with the extension of the optical path) we see a higher influence of the receiver noise thus leading to a decreased $CINR_{LINK}$ value,

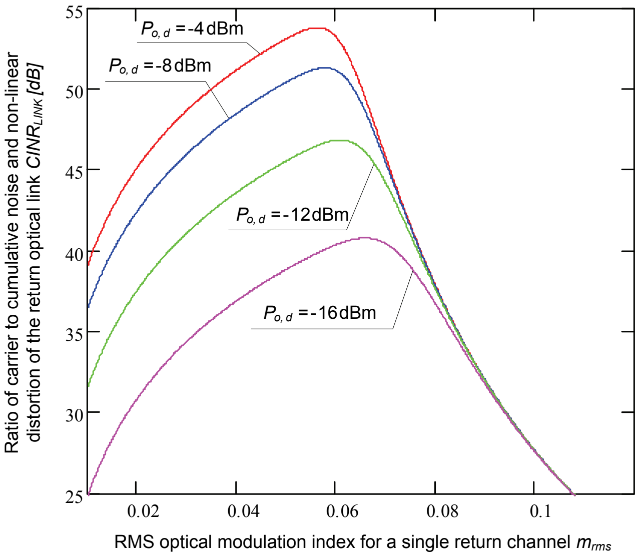

Fig. 3 Ratio of carrier to cumulative noise and non-linear distortion of an optical link $CINR_{LINK}$ w depending of the RMS modulation index for a single return channel m_{rms} for different received power levels $P_{o,d}$ at the input of the optical receiver (N = 15, B_N = 2,56 MHz, RIN = -145dB/Hz)

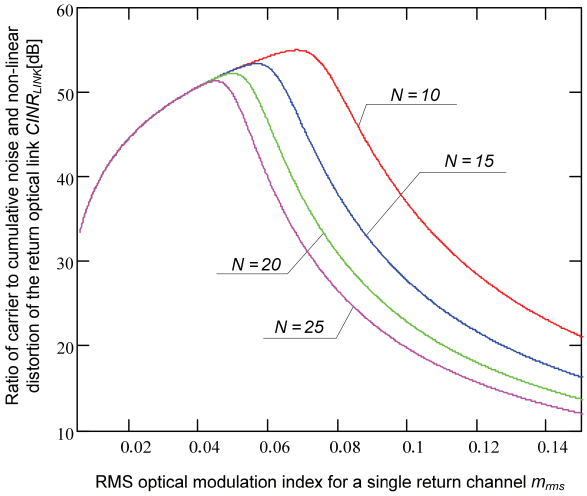

Fig. 4 Ratio of carrier to cumulative noise and non-linear distortion of an optical link $CINR_{LINK}$ w depending of the RMS modulation index for a single return channel m_{rms} for different numbers of return channels N ($P_{o,d}$=-5dBm, B_N=2,56MHz, RIN=-145dB/Hz)

b) a falling slope, starting at the m_{rms} value, at which the level of non-linear distortion caused by signal clipping at the input of the laser diode is higher than the laser link noise. With the further increase of the m_{rms} value, we get a rapid decrease of $CINR_{LINK}$. At the same time, when reducing the number of simultaneously transmitted return channels N we see a lowered level of non-linear distortion and the entire falling slope moves towards the higher m_{rms} values, which improves the dynamic range of the signal at the input of the optical transmitter,

2) the maximum value of function $CINR_{LINK}(m_{rms})$ moves towards the higher m_{rms} values, with the decrease of the optical power level at the input of the photodetector $P_{o,d}$, as well as with the decrease of simultaneously transmitted channels N. This means, that with the increase of the number of simultaneously transmitted return channels it is necessary to reduce the signal level at the input of the optical transmitter ,whilst with the increase of the optical path length, which leads to a lowered received power $P_{o,d}$, it is necessary to appropriately raise the signal level at the input and thus increase the optical modulation index of each of the return channels,

3) the optimal m_{rms} value for a planned return path system can be determined based on the $CINR_{LINK}(m_{rms},P_{od},N)$ plot for a given number of simultaneously transmitted channels N, which results from the data throughput (bit rate) assumed for each of the subscribers, along with the chosen modulation type and optical path attenuation (resulting from path length and wavelength) as well as other sources of attenuation, such as optical power splitters or WDM *(Wavelength Division Multiplexing)* multiplexers. The operating point should be chosen on the rising slope, in the middle of the dynamic range of the input signal for the required CINR and chosen modulation type.

Coax part of the HFC network

In order to define the carrier to noise and interference ratio $CINR_{ONU}$ at the input of the ONU node, we shall assume that the interferences are introduced into the network mainly from the inter-building networks and then are transmitted together with the signal through the coaxial distribution network. The noise and interference is summed together from all network trunks coming together to the single node of the coaxial networks tree trunk architecture.

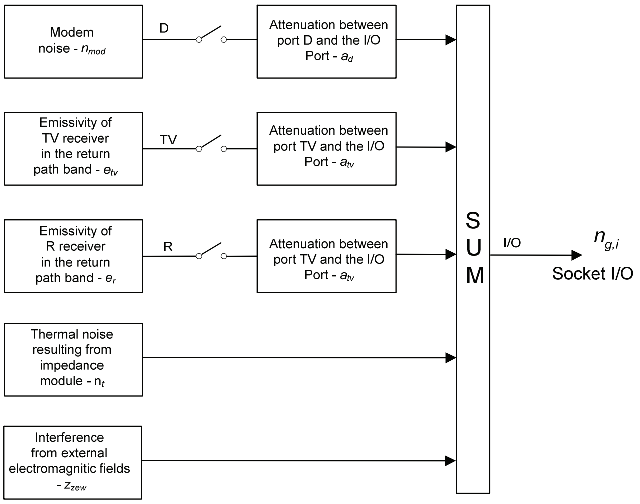

Fig. 5 Subscriber socket noise/interference model

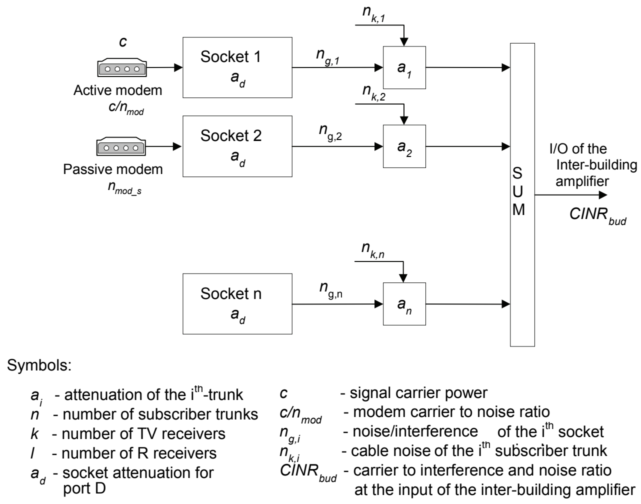

Fig. 6 Inter-building transmission network model

We also need to take into account the return path amplifier noise and distortion of the transmitted signal, caused by amplifier non-linearity. Fig. 5 shows the noise/interference diagram for a subscriber socket and then fig. 6 shows a diagram of a transmission network inside a building. Using the above diagrams, we present a universal relation [7] allowing for calculation of the carrier to noise and interference ratio for the inter-building network $CINR_{bud}$:

$$CINR_{bud} = 10\log\left(\frac{\dfrac{c}{\max(a_i)\cdot a_d}}{\sum_{i=1}^{n}\dfrac{n_t}{a_i}+\sum_{i=1}^{k}\dfrac{e_{tv}}{a_i\cdot a_{tv}}+\sum_{i=1}^{l}\dfrac{e_r}{a_i\cdot a_r}+\sum_{i}^{m-m_{sk}-m_{hk}}\dfrac{n_{\mathrm{mod\_}s}}{\max(a_i)\cdot a_d}+\dfrac{n_{\mathrm{mod}}}{\max(a_i)\cdot a_d}+\sum_{i=1}^{n}\dfrac{n_{k,i}}{a_i}+\sum_{i=1}^{n}\dfrac{z_r}{a_i}+\dfrac{m_{sk}\cdot z_{sk}}{\max(a_i)\cdot a_d}+\dfrac{m_{hk}\cdot z_{sk}}{\max(a_i)\cdot a_d}}\right) \tag{3}$$

where: m_{sk} = 0,1,2 is the number of neighboring channels, m_{hk} = 0,1 is the number of channels having a frequency *f/2*, where *f* is the frequency of the given channel (other symbols as in fig. 5 and 6).

The return channel amplifier carrier do noise and non-linear distortion ratio $CINR_{wzm}$ can be presented as [1]:

$$CINR_{wzm} = -10\log\left[10^{-\left(\frac{CNR_{wzm}}{10}\right)}+10^{-\left(\frac{NLDR}{10}\right)}+10^{-\left(\frac{CSO}{10}\right)}+10^{-\left(\frac{CTB}{10}\right)}\right] \tag{4}$$

where: CNR_{wzm} - carrier to noise ratio at the amplifier output, *NLDR* - carrier to non-linear distortion ratio (caused by amplifier signal clipping), *CSO* - composite second order, *CTB* - composite triple beat.

Equations (3), and (4) are universal and can be used in analyses of practically any building or distribution network topologies including amplifiers of different parameters. However, in order to calculate the carrier to interference ratio at the input of ONU node $CINR_{ONU}$ it is also necessary to take into account the summed interference from all individual network trunks. This can be performed step-by-step, by calculating the carrier and interference levels for the individual network nodes, however this approach would require tedious entry of vast amounts of information describing the network setup. One can avoid such work and estimate the $CINR_{ON}$ with sufficient accuracy if the network fulfills just a few requirements:

a) if the distribution network is based on identical amplifiers for the return paths,
b) if the path attenuation of individual network segments is appropriately compensated through the use of amplifiers,
c) if the amplifiers are of sufficient strength,
d) if fairly identical building network setups are used for each given building type.

Nowadays, a great majority of CATV networks fulfill the above conditions, thus the presented formulas can be used as a practical tool for calculating the transmission parameters of active return path coax networks.

Assuming fairly uniform building types at a given ONU region, the carrier to noise and interference ratio $CINR_{ONU}$ can be stated in the form of a relation [40]:

$$CNIR_{ONU} = -10\log\left[10^{\frac{CINR_{bud}-10\log\left(INT\left(\frac{L}{n}\right)\right)}{10}}+10^{\frac{CNIR_{wzm}-10\log\left[INT\left(\frac{L}{n}\left(1+\frac{1}{typ\_sieci}\right)\right)\right]}{10}}\right]-K(l_{bud}) \tag{5}$$

where: *INT* is a function returning the integer value of the argument, *L* is the number of subscriber sockets fed from the given ONU, *n* is the average number of subscriber sockets in the inter-building network for the network segment connected to the given ONU, *typ_sieci* ('network-type') parameter defines the subscriber distribution (spread) over the given region, *K(*l_{bud}*)* is used as correction, depending on the number of building networks l_{bud} connected to the given ONU.

Based on real $CINR_{ONU}$ measurements, it was determined that the correction *K* can be approximated using a linear function:

$$K(l_{bud}) = k\cdot l_{bud} \tag{6}$$

where: *k* is a constant ranging from 0,08 to 0,14.

For our calculations we have assumed *k* = 0,11. Using the relation (20) we have plotted carrier to noise and interference ratio $CINR_{ONU}$ for the input of ONU, assuming the return channel bandwidth of B_N =2,56 MHz, number of return channels *N* =15 and *L* =500, *k* = 0,11.

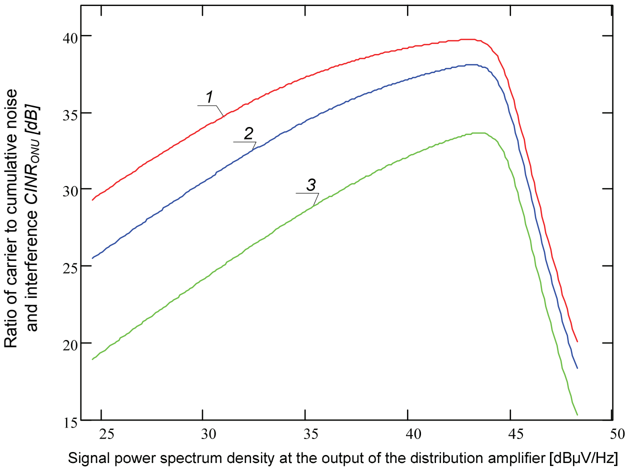

Fig. 7 Ratio of carrier to cumulative noise and interference at the input of the optical transmitter $CINR_{ONU}$ as function of the signal power spectrum density at the output of the return path distribution amplifier for: 1) dense urban zones, 2) average density urban zones and 3) low density urban zones.

The simulation results presented in figures 7 to 10, show that the best method for improvement of transmission parameters (measured as the ratio of carrier to cumulative noise and interference in the return channel) is to reduce the number of subscriber sockets per each ONU (fig. 8), irregardless of the area type (urban density) covered by the coaxial network. Analysis of the non-linear distortions present in the return path, additionally showed that there is a certain optimal composite signal power spectrum density (i.e. a signal comprising of a combination of several return channels) for which the carrier to noise and interference ratio will be the highest (fig. 7 to 10). It was also shown that because of a high level of interference from the building network compared to the low number of transmission channels, the low signal non-linear amplifier distortion has an insignificant effect onto system operation.

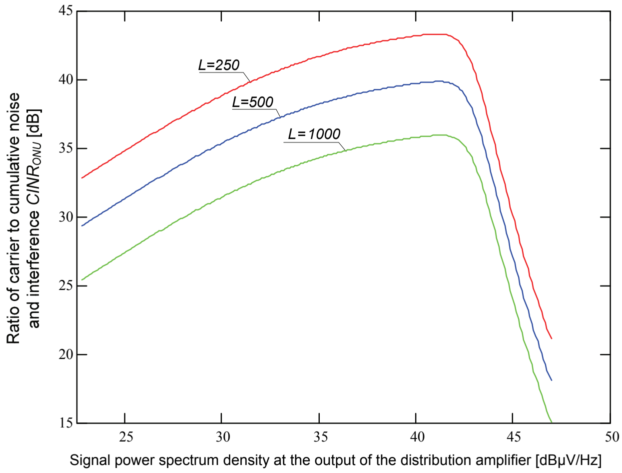

Fig. 8 Ratio of carrier to cumulative noise and interference at the input of the optical transmitter $CINR_{ONU}$ as function of the signal power spectrum density at the output of the return path distribution amplifier for different number of subscriber sockets per each ONU node, for a highly dense urban zone and assuming N = 15

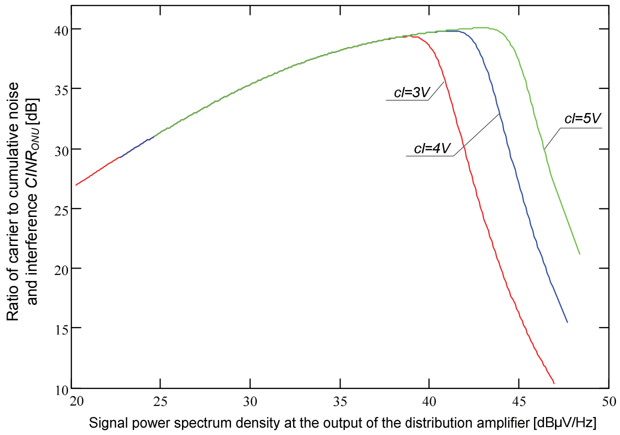

Fig. 9 Ratio of carrier to cumulative noise and interference at the input of the optical transmitter $CINR_{ONU}$ as function of the signal power spectrum density at the output of the return path distribution amplifier for different amplifier clipping limit levels, for a highly dense urban zone and assuming L = 500, N= 15, B_N= 2,56MHz

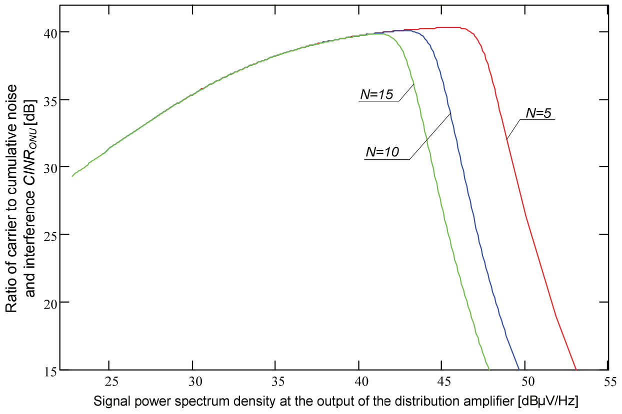

Fig.10 Ratio of carrier to cumulative noise and interference at the input of the optical transmitter $CINR_{ONU}$ as function of the signal power spectrum density at the output of the return path distribution amplifier for different number of return channels N for a highly dense urban zone and assuming L = 500, B_N= 2,56 MHz

On the other hand, an important aspect limiting the return channels dynamic range is amplifier saturation, which leads to clipping of the high-power multichannel signals. By increasing the amplifier clipping limit *cl* we achieved improved dynamic range at the output of the amplifier (fig. 9). Another important aspect is the relation of the number of return channels *N* and the signal power spectrum density at the output of the distribution amplifier (fig. 10). As one can see, an increase of the number of return channels leads to reduced dynamic range of the distribution amplifier output and requires reduction of the signal power spectrum density as the number of simultaneously transmitted channels increases. At the same time, the reduced signal power spectrum density causes a lower carrier to noise and interference ratio, thus reducing the potential throughput capacity of the return path.

Summary

The paper presents a method for calculation of the HFC cable TV network return path performance. It shows that it is possible to relate the network topology to carrier to noise and interference ratio, and thus calculate the potential and actual throughput of the return path. The presented return path model allows for assessment of the foreseen per subscriber bit rate, depending on the number of subscribers served by the given ONU, subscriber distribution (urban density) and parameters of the network components.

This paper also confirmed that the return path performance depends mainly on:

a) For the optical part of the HFC network – proper matching of the optical transmitter power to the attenuation characteristics of the link as well as selection of operating parameters of the optical transmitter, depending on the number of transmitted return channels,

b) For the coax part of the HFC network – proper selection of the number of subscriber sockets leading to a single ONU node, depending on the number of transmitted return channels, subscriber distribution and return path amplifier settings.

REFERENCES

[1] Ciciora W., Farmer J., Large D., Adams M., Modern Cable Television Technology, *Morgan Kaufmann Publishers* 2004

[2] Raskin D., Stoneback D., Broadband Return Systems for hybrid fiber/coax cable TV networks. *Prentice Hall PTR*.1998

[3] Carro B., Nguyen Chan H., Sanchez A., Link-Level Effect of Noisy channel over data transmission on the return path of an HFC network, *IEEE GLOBECOM '01,* p. 425 – 429, vol.1 IEEE 2001

[4] Bonang Ch., Bringing Home Bandwidth: Optimal HFC Access Architectures for New Builds, *Harmonic Inc. White Paper* www.harmonicinc.com ,2004

[5] Cox Ch. H., Analog Optical Links Theory and Practice, *Cambridge University Press* 2004

[6] Królikowski R., Analiza łącza optycznego z bezpośrednią modulacją intensywności światła w systemach TVK, *Krajowa Konferencja Radiokomunikacji, Radiofonii i Telewizji KKRRiT 2005*, 15-17 Czerwca 2005, Kraków

[7] Królikowski R., Analiza wpływu parametrów i topologii sieci telewizji kablowej na pojemność informacyjną toru zwrotnego), *Rozprawa Doktorska*, Instytut Telekomunikacji i Akustyki, Politechnika Wrocławska, Kwiecień 2006

Autor: dr inż. Rafał Królikowski, Politechnika Wrocławska, Instytut Telekomunikacji, Teleinformatyki i Akustyki, ul.Janiszewskiego 7/9, 50-372 Wrocław, E-mail: rafal.krolikowski@pwr.wroc.pl.