APPLYING NEW TECHNIQUES TO IMPROVE ANALOG-TO-DIGITAL LINK PERFORMANCE—THE ROLE OF DIGITAL SIGNAL PROCESSING

Venkatesh Mutalik, Marcel Schemmann, Craig Malone,
Zhijian Sun, Long Zou, Mary Margaret Ong, Alexei Chkourko
Philips Broadband Networks

Abstract

Analog-to-digital conversion techniques are finding increasing application in HFC transmission networks as a means of transporting analog signals reliably. Among the advantages of these techniques are a range of multiplexing options, mass-produced devices, and the ability to perform additional signal processing in the digital domain.

The role of Digital Signal Processing (DSP) in an analog-to-digital converted CATV system may be divided into two broad sections. In the first, the processing is independent of the specific nature of payload (e.g., the data could be of QPSK, QAM16, QAM64 or QAM256 types). Here, we would primarily be designing general compression schemes as well as automating various self-test and EMS routines, activities which are roughly independent of the digitized information content. In the second, the signal processing can take advantage of known characteristics of the payload data. For example, here, we would be interested in designing appropriate filters, demodulators, and other devices more appropriate for distributed CMTS-type applications.

The authors have implemented a hybrid combination of Digital Signal Processing (DSP) and traditional RF technology to improve HFC return path performance. This approach uses an A/D optical return path transmitter and receiver which, in addition to normal "brute force" coding, adds DSP algorithms that enhance the achievable dynamic range and conserve bit rate. Test results on prototypes show dramatic improvement in Noise Power Ratio (NPR), and simulations closely match the measured performance.

This paper will present some of these results and address digital signal processing of the payload agnostic type. It will also describe some of the technical details in relation to currently available digital return systems.

INTRODUCTION

In the HFC CATV return band, systems suffer from several noise sources in the cable plant and in the optical links. Noise from the cable plant can be bursty and concentrated at several frequencies [1]. This noise is determined by the existing cable plant and can not be reduced by a transmitter.

However, a transmitter needs modulation headroom before the clipping point to accommodate noise bursts in some channels without affecting other channels. Noise in the optical links stems from laser RIN, shot noise, and receiver thermal noise, and it can be incurred several times if the signal is re-transmitted. State-of-the-art analog transmitters use selected 1310 nm DFB laser transmitters and can achieve an acceptable signal-to-noise ratio with headroom over a limited link length of about 30 km from the node to the hub.

Analog-to-digital conversion followed by digital transmission of the converted data has been proposed as a method to overcome the analog noise sources and thus relax laser requirements, increase transmission distance, and provide a more robust re-transmission capability. Such schemes require very high data rates to achieve an acceptable transmission quality, and results obtained so far at lower rates yield marginal performance.

In this paper, the requirements for the transmission data rate and clock jitter are discussed for a dual RF channel input digital transmitter. Then a DSP algorithm is proposed that allows reduction of the total data rate to fit existing OC-48 standards with excellent transmission quality. The limit for acceptable performance is explored, and results are compared with test data. We further discuss the link budget requirements and DWDM system requirements for a fiber-conserving system that operates on the ITU grid. The data reduction provides enough room for the addition of bits for FEC and DC balancing, which results in an extremely high link budget and transmission distance. Digital control provides excellent wavelength stability up to and exceeding an 85° C module temperature environment, with reduced power dissipation.

System description

The return transmitter operates from a node. In the field, internal node temperatures in the range of –40° C to +85° C can occur. In a system where, for example, 32 nodes are to be combined into a single fiber with 0.8 nm (100 GHz) spaced ITU channel lasers, a ±0.1 nm wavelength stability is required for the transmitters.

Use of a DWDM combiner in the field would put very strict requirements on its temperature performance. For this reason, we propose using a passive coupler. For 32 channels, a 12 dB loss is to be anticipated. The maximum fiber span for modem operation is assumed to be 100 km, which yields a 20 dB fiber loss (0.2 dB/km). Finally, in the headend, a DWDD is assumed with a 6 dB implementation loss. This yields a total loss of 38 dB. Figure 1 depicts the described system. A comparison of the two scenarios [2, 3] indicates savings on transmitter receiver pairs, wavelengths, capacity, cost of the DWDM, and the cost of erecting and maintaining the hub.

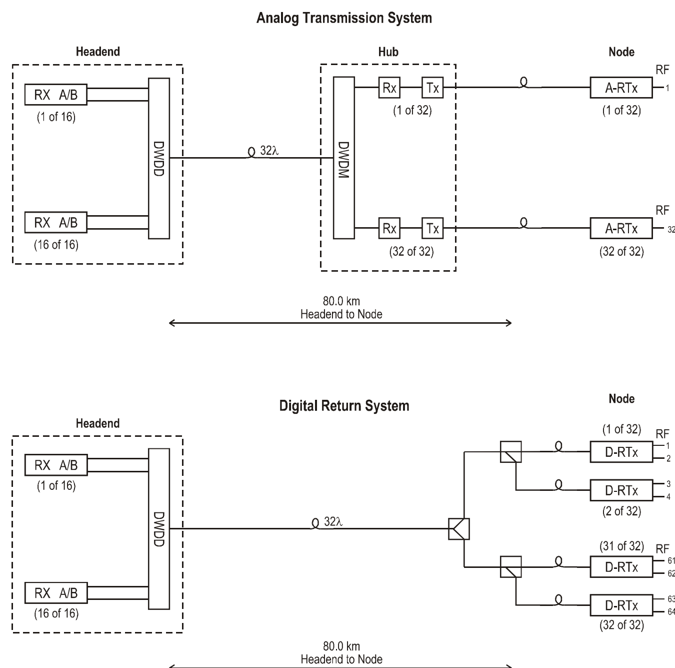

Figure 1. Comparison of analog and digital return transmission system architectures

Basic implementation

Optically, this link requires a low chirp DWDM OC-48 laser with a 7 dBm average output power and typically 1 dB dispersion penalty at 100 km. The receiver requires an APD detector with a –32 dBm sensitivity to obtain the required budget and link length.

The analog to digital converters digitize two RF input channels operating in the 5..42 MHz band (or 5..48 MHz in FTLA systems). The minimum sampling rate is twice the RF bandwidth and thus should be above 100 MHz. A typical requirement on the attainable signal-to-noise ratio as determined by an NPR test is 40 dB. This NPR is to be maintained in a dynamic window of at least 15 dB [4]. This is investigated in the next section.

THEORY AND SIMULATION

Effective Modulation Depth

Optical, RF, and digital performance are all related by a parameter called the Effective Modulation Depth (μ_{eff}) for the A/D converter. This μ_{eff} is a counterpart of the more familiar Optical Modulation Depth (OMD) frequently encountered in optics literature. Just as the laser is a compressing entity in the optical domain, so too is the A/D converter to the digital system. It may be noted that for digital optical transmission, an OMD exists as well for the laser, but a well-designed transmission system does not have any impairment due to the OMD of the laser as a function of input RF power.

In order for the system to obtain some required performance, a minimum Effective Number of Bits (ENOB) is required from the A/D converter. Note that this number is smaller than the Number of Bits (NOB) of the A/D converter due to non-linearities in the A/D converter [5].

As illustrated in Figure 2, for a multi-channel RF input signal, an effective modulation depth (μ_{eff}) of close to 30% leads to significant clipping distortion.

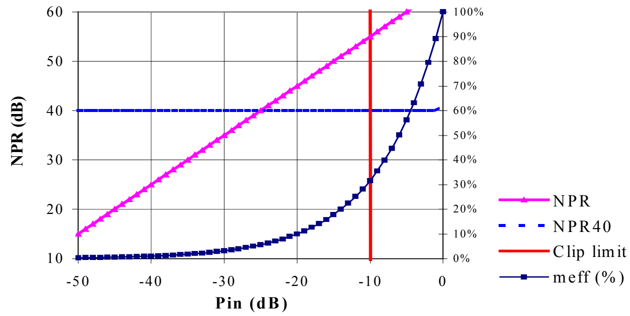

Figure 2. NPR and μ_{eff} as a function of RF power

To meet the 40/15 NPR requirement, one should try to obtain a 40 dB NPR at 15 dB below the A/D converter's clipping point. Hence, for μ_{eff} = 30%, a minimum signal-to-noise-ratio of 55 dB is required (disregarding clipping impairments). This translates to 62 dB for a single tone with a 100% amplitude modulation index (71% μ_{eff}) and requires an ENOB of 10. Consequently, the NOB must be 11 or higher.

The sample and hold (S/H) timing jitter should be approximately 15 ps to prevent ENOB degradation from sampling jitter. In order to satisfy the ENOB requirements, a 12-bit AD converter is needed. A sampling rate of 103.68 MHz is used to simultaneously meet the Nyquist condition and be a perfect match for the OC48 transmission rate. The total data rate is then calculated as follows:

2 channels x 12 bits x 103.68 MHz = 2.488 Gb/s

This is the exact OC48 standard data rate. Hence, cost-effective components are available for the link. Notice, however, that there is no overhead left for word synchronization, DC balancing, error correction, and status monitoring.

Simulation routine

The system performance of a system with multiple RF carriers and with an NOB of 12 and a sampling jitter of 15 ps rms can be numerically estimated by sampling and digitizing a set of carriers with 2^{ENOB} levels. By taking the Fourier transform of the resulting set of data, a spectrum results.

In the input spectrum, a slot is left out. The timing jitter and the quantization noise generate spectral content in the slot. Comparison of that power to the carrier power yields an estimate of the anticipated NPR and is displayed as the output of the simulation.

DIGITAL SIGNAL PROCESSING

Thus far, a general description of the digitizing and recovery process has been explained. It is well known, however, that some overhead is required in digital transmission to effectively transmit information. The only possible way out of such activity is by somehow reducing the amount of required information payload from the current OC48 data rates. Doing so, however, requires either a reduction in the number of bits or a change in the sampling frequency, neither of which is conducive to required performance. Therefore, some techniques have to be applied to protect the performance as well as to allow some leeway for data processing.

Test results

The number of bits required to digitize the input signal can be reduced by suitably processing the signal before it is digitized such that a converter (e.g., 10-bit AD) can be applied. However, this leads to large distortions, so an inverse operation is required at the receiver side.

The input signal range is reduced at the transmitter side. The operation is inverted at the receiver side. This results in an enhancement of the quantization noise for large input power such that degradation in SNR is expected. However, for large input power, the signal is very far above the quantization noise, so the performance is acceptable.

A serious lingering problem with this method is that to maintain a 40 dB NPR, an extremely good match between the analog compressing and de-compressing circuitry is required, which is not practical over the operating temperature range. For this reason, 12-bit A/D and D/A converters have been chosen, and the DSP algorithm operations are done in the digital domain. Using the method outlined above, expected NPR performance is calculated for compression from 12 to10 and 8 bits.

Obviously, a 10-bit algorithm scheme is possible with significant margin over the required NPR performance. Even down to 8 bits, the required NPR performance can be met. The efficient algorithm scheme frees up bits that can now be used for overhead. These are now used for addition of FEC and DC balance of the code. NPR test results for 12 to 10 and 12 to 8 bit compression are shown in Figure 3 for a transmitter with 7 dBm output power (10 dBm peak) and an APD receiver on a 100 km fiber link.

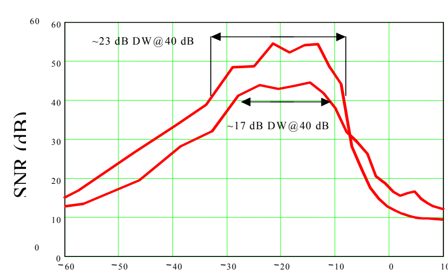

Figure 3. Estimated NPR performance of a digitally processed system

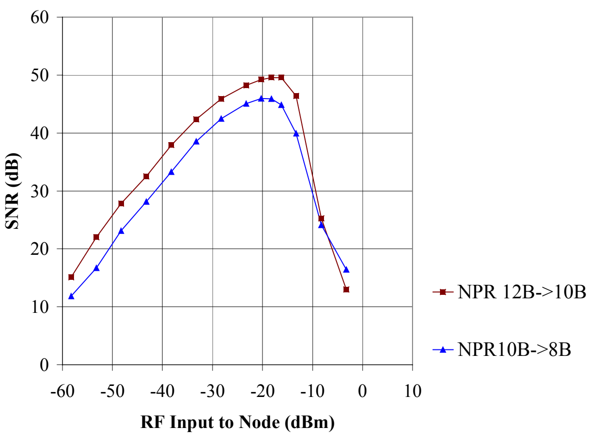

Figure 4. NPR test results for 12 to10 and 10 to 8 bit digitally processed systems

Figures 3 and 4 reveal excellent agreement between model and test data; for a 12 to10 bit transformation, 40 dB NPR can be obtained in a 20 dB dynamic window, which well exceeds the requirement.

The curve presented in Figure 5 shows performance at different link budgets using FEC for the digital link. Using the available overhead and signal processing allows operation well above the required link budget. No performance degradation is observed up to 41dB budget, and the link is maintained up to 44dB budget. The FEC allows monitoring of the error rate, and the system is switched off if a 20 dB SNR cannot be maintained at the clipping side.

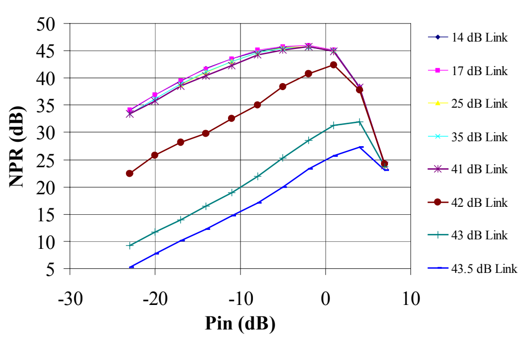

Figure 5. NPR test results of a 12 to 10 bit digitally processed system over various link budgets

In Figure 6, QPSK and 16 QAM error rates are plotted for comparison with the NPR curves [6]. On the noise side, the BER and SNR curves yield the same result. On the clipping side, the BER is degraded at a lower power level due to the non-Gaussian nature of clipping noise.

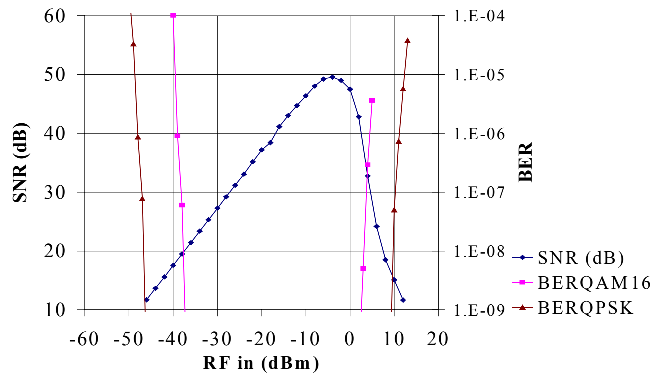

Figure 6. NPR and BER test results of a 12 to 10 bit digitally processed system

Digital control of laser temperature

The presence of a powerful DSP processor also allows intelligent control of the laser Peltier element in a full bridge switch mode power supply configuration. The DSP can be programmed to minimize dissipation and switching noise through intelligent control of the switches. The resulting wavelength stability and power consumption is plotted in Figure 7.

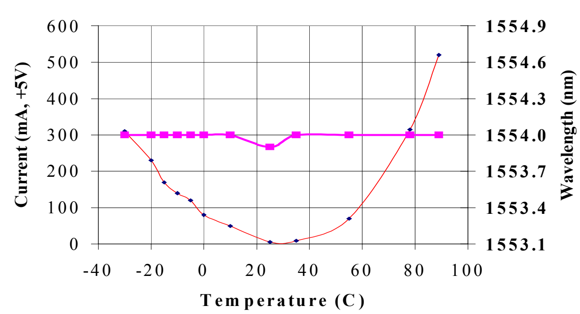

Figure 7. Test data of wavelength and power consumption as a function of module temperature

Clearly, the laser wavelength can be maintained well within limits up to 90° C module temperature. The power consumption that is required to cool the laser is as low as 3W up to 85° C module temperature.

The NPR performance of the system over temperature shown in Figure 8 demonstrates the power of DSP in maintaining system performance over temperature. An ambient node housing temperature of 60° C presents itself as 85° C for the transmitter module.

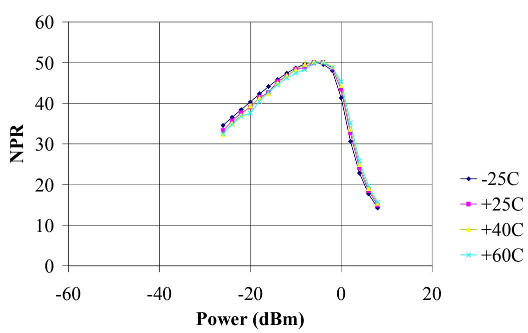

Figure 8. NPR test results of a 12 to 10 bit digitally processed system over ambient node temperature

The DSP monitors the laser temperature and switches off the laser power in case the wavelength is out of range; thus, neighboring channels will not be affected. It also monitors the cooler current consumption and limits that to prevent overloading the power supply.

CONCLUSION

A dual channel AD CATV return band transmitter was presented operating on the ITU grid. Requirements were derived for an EDFA free operation of a return system that combines 64 individual return channels on a single fiber and transports these over 100 km of single mode fiber.

It was shown that at least a 12-bit A/D converter is required for acceptable operation, resulting in an excessive requirement of the total data rate. An information efficient algorithm was then implemented with 10-bit transmission in a DSP to obtain 40 dB NPR in a 20 dB dynamic window combined with code balancing.

An additional algorithm is proposed that allows a 40 dB NPR in a 15 dB dynamic window with only 8-bit transmission. The digital link FEC allows a link budget in excess of 40 dB and link lengths in excess of 150 km. Further application of the DSP to the control of the laser cooler has yielded better than 0.1 nm wavelength stability in the –40° C to +90° C degree temperature range at a power consumption of only 3 W at 85° C module temperature.

Similar success with respect to NPR performance has been achieved with un-cooled DFB lasers with distances approaching 80 km.

Clearly, the application of DSP can significantly improve the performance of digital return systems

ACKNOWLEDGEMENTS

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