# Optical Access Key featuring Low-power Electronic Adaptive Function (OAKLEAF)

University of Essex (GR/R32819/01) and University of Cambridge (GR/R32802/01)

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## 1. Introduction

As envisaged by the OAKLEAF proposal in 2002, the bandwidth requirement in the UK market has indeed rocketed in the past few years. The number of broadband connections has surpassed the dial-up connections count and the broadband penetration has increased fifteen fold in the past three years[1]. The OAKLEAF proven hybrid copper/fiber access solution is being heavily investigated by service providers, giving ample opportunities for well published and recognised research to be implemented in real time for the benefit of the broadband market.

Fibre-to-the-home (FTTH) provides the ultimate wireline access medium due to its effectively unlimited bandwidth. However, without significant opportunity for new revenue generation, for example through high uptake rates of triple play services, the economic model for wide-scale FTTH deployment remains weak. The business case for fibre-to-the-curb or cabinet (FTTC) deployment is however much stronger. Here the fibre cable replaces much of the existing copper link but leaves the final copper drop-link untouched[2]. The cost advantages are therefore drawn from increased sharing of the fibre plant, greater reuse of existing infrastructure and lower installation and purchase costs of the end user (CPE) equipment. Moreover, data rates of very high rate digital subscriber line (VDSL) and the spectrally enhanced VDSL2 technologies can now exceed 100MBps symmetric transmission over relatively short distances (up to ~300m), making it an ideal transmission format for FTTC deployments. In the upgrade of legacy access networks, very high speed Digital Subscriber Line (VDSL) may prove to be one of the enabling technologies for providing high bandwidth FTTX [3].

## 2. Key Advances

### 2.1.VDSL Transmission over a Fibre Extended Access Network

In this section we describe the novel work done in order to prove the technical and economical feasibility of hybrid copper/fibre access network for provision of wide scale broadband services.

### 2.1.1.System Architecture and Performance Analysis

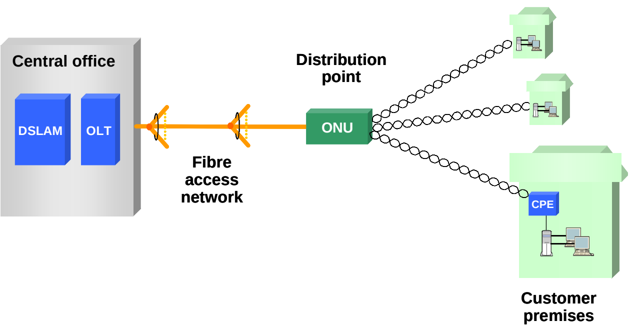



Figure 1: Network architecture used for DSL over optics

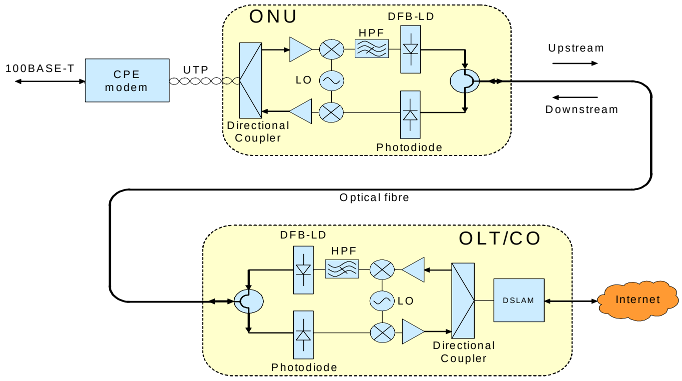



Figure 2: VDSL over FTTC experimental setup

The FTTC network in Fig.1contains some key feature, amongst which are the compatibility with PON architectures and the retention of the DSLAM equipment in the Central Office. The OLT/ONU hardware have been designed to operate at low power with a small footprint, making them compatible with the legacy cabinet and distribution point infrastructures (fig. 2.)[4,5]. The ONU multiplexes each of the DSL signals from the customer premises equipment (CPE), with a maximum of 24 VDSL bandwidth signals expected to be contained within a 1 GHz modulation bandwidth optical carrier using the current implementation. Future designs may encompass single/vestigial sideband techniques to improve the spectral efficiency of the subcarrier signals.

Results obtained demonstrate two key experimental observations. Firstly, the transmission performance of the each VDSL signal over a range of subcarrier multiplexed channels can be assessed across the approximate frequency range 50-1000MHz, principally governed by the mixer bandwidth. Secondly, performance across increasing optical distance can be observed. Fig. 3 shows baseline performance of the modem transmission rate through the ONU/OLT equipment for a range of subcarrier frequencies. The results of Fig. 3 indicate a mean downstream rate of 46.4 Mbps and an upstream rate of 24.1 Mbps, these compare to the 67 Mbps and 40 Mbps respectively available to the fast-998 band plan used, correspond to transmission efficiencies of 69% and 60% respectively. The decreased efficiency results almost exclusively from the up- and down-conversion processes, namely the conversion loss of the

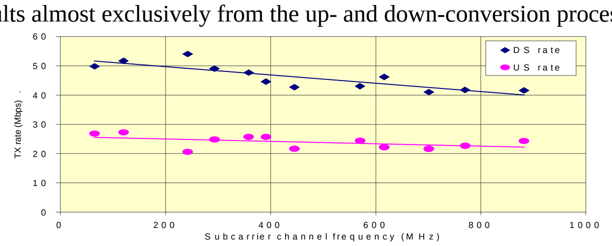



Figure 3: Baseline data rate versus subcarrier frequency though the OLT+ONU interface

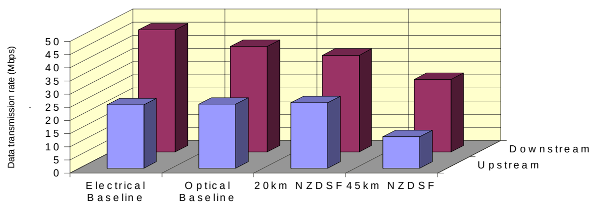



Figure 4: Mean data rate across subcarrier spectrum over increasing transmission distance

mixers which can be improved by linearization techniques. To measure transmission performance over the fibre optic extended link, the setup of Fig. 2 was used with increasing lengths of NZDSF fibre and again performance was measured as an average across the full subcarrier spectrum. The results for baseline optical (i.e. a patchlead), 20 km and 45 km of the SM fibre are plotted in Fig. 4. The results, as expected, show a gradual decrease in the data rate with distance reducing the mean downstream rates to 37 and 28 Mbps for 20 km and 45 km respectively whilst the upstream rates are reduced 24 and 12 Mbps for the same respective distances. In keeping with the expected access topologies no optical amplification was used. The results therefore follow a predictable degradation due to the increased losses (rayleigh scattering) and their consequent reduced SNRs as received by the modems.

### 2.1.2.Auto Link Optimisation of Hybrid Copper/Fibre Optical Link

Large-scale deployment of the hybrid copper/fiber system will require a cost and time efficient approach. Also the changes in the laser characteristics with temperature variation and material degradation will need to be corrected in the long run. A novel system that can automate the process of remotely (from CO) controlling and establishing a link by changing the bias current of the semiconductor laser in ONU (in cabinet) was developed. This system can be used to power-up any kind of laser as it is capable of automatically finding the threshold and optimum bias current for maximum throughput. The system was tested successfully on two uncharacterised lasers at room temperature and the link was established in less than 25 minutes[5]. Figure 5. shows the algorithm to control the laser bias. The bias current was incremented by 0.3mA in every iterartion of the loop. The response from the CP equipment was received at 1.5-1.9mA with

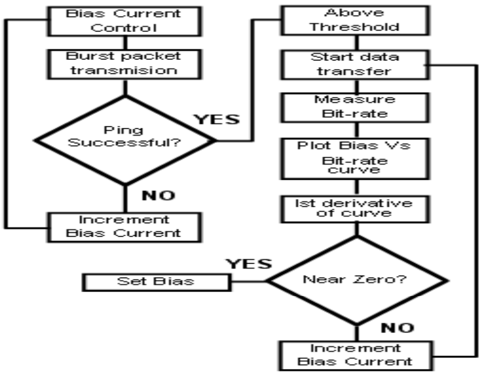



Figure 5: Optimization algorithm

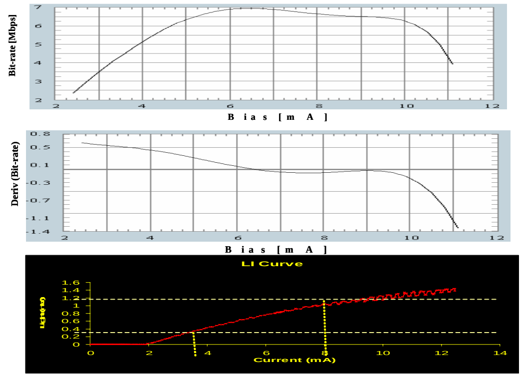



Figure 6: Automatic bias setting using the algorithm

average transmission time of 95millisecond. This is the region when the laser has crossed its threshold level and link is established. The near-zero loop starts and measures bit-rate at different bias current levels by further incrementing the bias current. 15Mb of data was transferred at each bias level. The bias versus Bit-rate curve was plotted (Figure 6). It can be observed that at 5.8mA bias current above threshold, the bit-rate peaks and becomes constant. It will start dropping again as the bias current nears saturation. The first derivative of the curve in Figure 6. will be in the proximity of zero as the bit-rate remains constant. Newton-Raphson method is used to find the zero-point. This zero-point occurred at 7mA. The system finally sets the bias of the laser and the link is finally optimised.

### 2.1.3.Super DMT

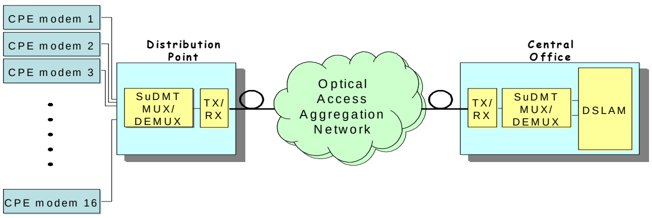



Figure 7: System concept

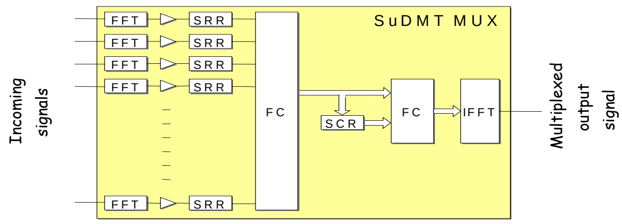



Figure 8: Schematic of SuDMT multiplexer

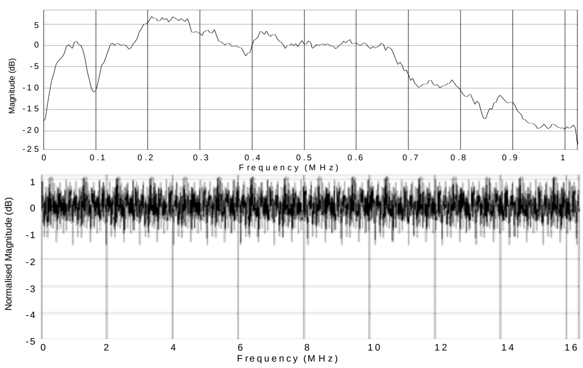



Figure 9: Power spectra (a) after transmission of the ADSL signal through the UTP and (b) after multiplexing of 16 ADSL signals by the SuDMT

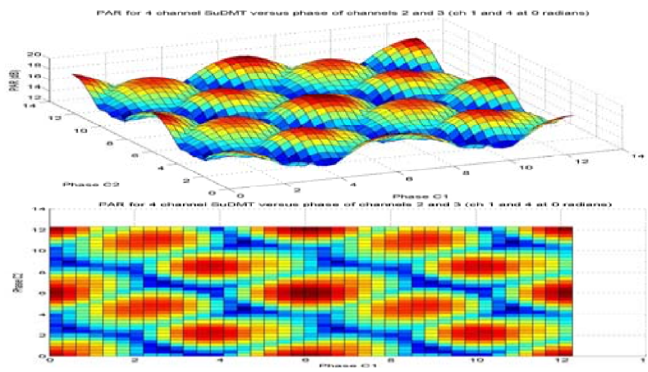


Figure 10: PAR for 4 channel SuDMT versus phase of channels 2 and 3

A novel DMT based scheme for the multiplexing and demultiplexing of up to 24 xDSL signals in the DP was simulated (fig. 7.)[6]. This solution can be implemented using current DSP processing technology and furthermore provides an efficient signal for the direct modulation of a low cost semiconductor laser. The scheme provides the possibility of a single chip solution for a fibre connected DP, with the added advantages of being both inexpensive and of having low electrical power requirements. In the current model, we demonstrate the technique by combining/splitting 16 ADSL signals, as shown in Fig. 8. The scheme is also suitable for carrying VDSL signals with equal efficacy, and indeed even a mixture of various xDSL ‘flavours’. Fig. 9(a) shows the spectrum of the ADSL signal after transmission through the simulated UTP., and 9(b) the spectrum of the multiplexed 16 ADSL signals after FEQ and digital multiplexing, as applied to the laser transmitter prior to transmission over the fibre link. The flat response of the aggregated SuDMT signal compared with the received ADSL signal is due to the spectral normalisation applied by the DSP. Over a distortion free optical link the data transmission operates error free, thus verifying the correct operation of the concept. This system is spectrally more efficient in comparison to the analogue SCM scheme, as it would occupy ~4 times this bandwidth (allowing for the second sideband and 100% guard bands). Higher PARs result in higher error rates and consequently lower data transmission rates in the presence of nonlinear transmission components, hence reducing the PAR will improve performance. Applying a phase offset to each component of the Fourier transformed signals in the SuDMT multiplexer has a significant effect on the PAR of the launched signal, reducing it by up to 5dB. Fig. 10 shows Graphs depicting the variation of PAR with inter-channel phase offset applied to the inner two channels (2,3) of the 4 channel system simulated. The peaks reach around ~18.5dB and the troughs around ~13.5dB.

## 2.2.FTTC VDSL Transmission over Latin Routed DWDM Optical Access Networks

We tested an AWG based access network architecture for sub-carrier multiplexed VDSL transmission(fig. 11)[7]. This has been achieved using VDSL modems with in-house developed Optical Network Units (ONU). The ONU contains a 1550nm DFB laser and low-power electronics, all of which remain stable over a wide temperature range.

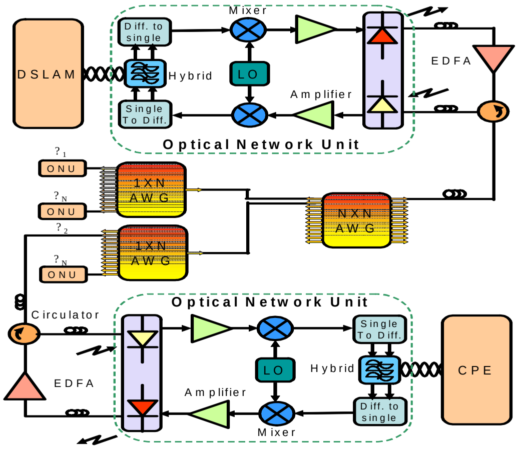



Figure 11: Block diagram for baseline optical transmission

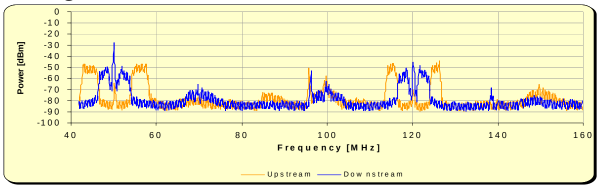



Figure 4: Subcarrier China bandplan VDSL upstream-downstream at 50MHz &120MHz, for a single wavelength

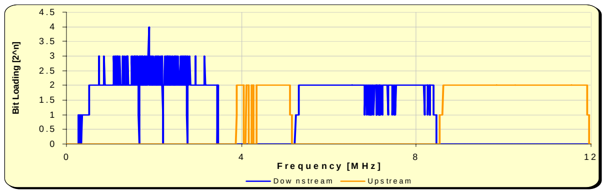



Figure 12: Bit-loading curve for 12 MHz bandplan 998

The same optical path can be used for both downstream and upstream data transmission between the CO and Customer Premises Equipment (CPE). This VDSL-WDM scheme can support a large number of customers (12,288), using a small number of wavelengths (32), by reusing the wavelengths at the cascade stages and exploiting the free spectral range of the AWGs, thus giving cost and complexity advantages over similar VDSL-WDM networks. Furthermore, this design can provide high speed services comparable with FTTH deployments, over the legacy access network infrastructure, thus making it a potentially more cost effective solution for near-term upgrade. With the arrival of VDSL2, symmetric 100Mbps service can be provided to the customer premises enabling triple-play provision. Fig 12(a). shows 2 China bandplan VDSL channels on one wavelength on a single mode fiber. Fig. 12(b). shows the waterfilling curve for fast VDSL 998 channel transmission.

## 2.3.Reflective Optical Network Unit

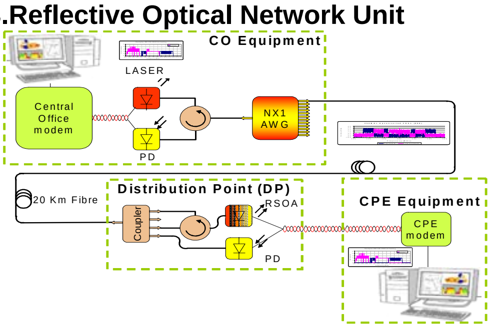



Figure 13: Reflective CP and CO setup in laboratory

| Device | Laser | RSOA | RSOA ASE | OSNR |
|---|---|---|---|---|
| Optical Power [dBm] | 4.53 | -4.23 | -30.22 | 25.99 |
| UP/DOWN-stream power levels [dBm] | Optical Power | | Device Attenuation | |
| | DOWN | UP | DOWN | UP |
| After Circulator | 2.79 | -19.01 | 1.74 | 1.72 |
| After 20km fibre | -1.28 | -17.29 | 4.07 | 4.08 |
| After 32X1 AWG | -6.19 | -13.21 | 4.91 | 9.17 |
| After RSOA branch | -10.89 | 0.62 | 4.70 | -11.67 |
| After PD branch | -11.05 | -19.01 | 4.86 | |

Table 1: VDSL optical power levels

The first demonstration of VDSL transmission using an Reflective semiconductor optical amplifiers (RSOA)[8,9] (Opto Speed 1550D4-R033) and DFB laser at 1544nm was done in our laboratory. The network architecture, based on AWG's, demonstrates the compatibility with WDM FTTH and suggests a possible upgrade path from FTTC. In particular, triple play was achieved on >20km singlemode fibre at data-rates of 48/25Mbps [10]. Future WDM based FTTH architectures will require minimal alteration to customer premises equipment (CPE) or the optical network unit (ONU. RSOA may become a key component to enable this VDSL based FTTC to WDM based FTTH transition. RSOA's ability to reflect and transmit at any wavelength from the CPE or ONU can dramatically reduce the compatibility issues. The combination of uncooled VCSEL at CO and VCSOA at the CPE could provide an inexpensive WDM FTTH solution. Fig. 13 shows the laboratory setup and table 1. gives the optical power levels at various points of the optical system.

## 2.4.Evolutionary Upgrade Path for Broadband Access Networks

We developed the idea of a three-stage upgrade path from a hybrid Fibre To The Curb (FTTC) solution, combining fibre and VDSL [2], to a final all-optical FTTH solution, offering advanced routing and bandwidth allocation features (fig. 13)[3]. A Fibre To The Building (FTTB) solution for switched LAN Ethernet services is an intermediate stage in this upgrade path [4], which incorporates fibre on the outside plant gradually to spread deploying costs and make the solution scalable. High density is also taken into account by using Wavelength Division Multiplexing (WDM) to multiplex different data channels in the optical layer on the same fibre. For the FTTC approach, we propose analogue Sub-Carrier Multiplexing (SCM) to accommodate several VDSL channels on a single wavelength. For the FTTB approach, we use the same basic SCM technique, but using digital signal processing to achieve better electrical spectrum efficiencies in order to transmit a larger number of channels on the same optical channel. Finally, for the FTTH approach, a hybrid WDM / Time Division Multiplexing (TDM) technique featuring advanced bandwidth allocation is presented.

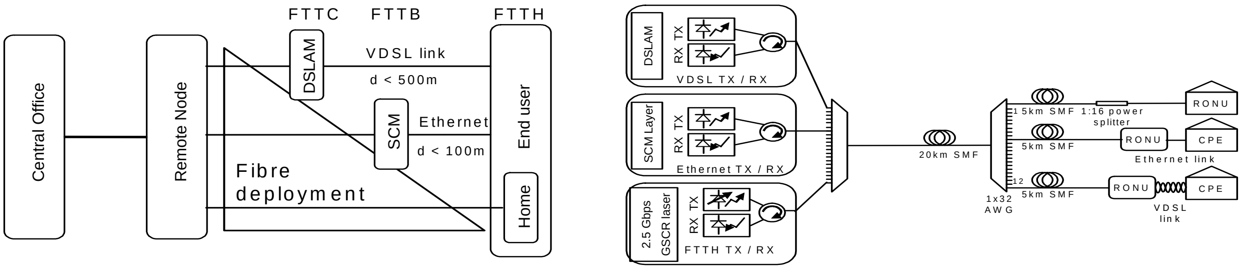



Figure 14: (a) Upgrade path stages (b) Network testbed

This solution enables the network to deliver bandwidth on demand and maximize optical resource utilization efficiency (fig. 14). The upgrade path is designed to be implemented from the Central Office (CO) to the end users, therefore all three approaches are based on WDM to multiplex several users on the same wavelength, although each of them use alternative multiplexing techniques on each wavelength depending on the number of users and the technology that is used for the last segment of the communication to the users.

## 2.5.System Simulation for Transmission of VDSL-QAM signals

Transmission of VDSL-QAM signals places severe demands on the linearity of the entire optical fibre system [11]. In order to analyse the effects of typical VCSEL non-linearities in a bandpass modulation context a simulation study was carried out on an 8-channel optical sub-carrier modulated QAM-VDSL system (Honeywell HFE 439x-541), using the *VPI transmission* simulation package [12].

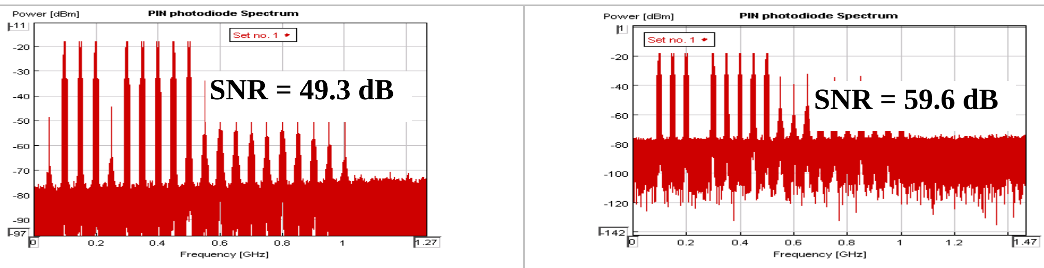


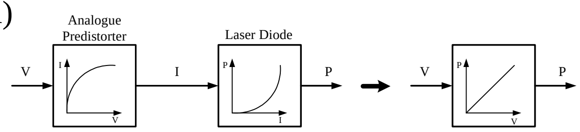

Figure 13: Simulation of typical VCSEL showing SNR improvement due to non-linearity compensation

The results (Fig. 13) show a two-tone spectrum plot with intermodulation distortion (IMD) and harmonic distortion (HD) due to laser nonlinearity. Theoretical analysis showed that higher order modulation products due to the QAM subcarriers are in equilibrium phase with those arising from other mixers; under appropriate conditions, third order nonlinear harmonics will coincide with second order nonlinear harmonics. If these are mutually out of phase, some cancellation of the distortion components at those frequencies will occur. A similar argument applies to higher-order distortion products. By this means, SNR performance can be significantly improved. Another approach suggested by this work is the use of pre-distortion [12] for linearisation of directly-modulated VCSEL lasers. This may be applied by digital or analogue means, using an electronic driver circuit designed to apply a nonlinearity having the inverse transfer characteristic of the device. Simulation results suggest that overall system linearity might be improved by 6dBc.

## 2.6.VCSEL Modulator-Driver for Wideband Optical Fibre Link

The laser diode and photodiode device in the access system link are intrinsically non-linear devices, though the laser diode generally dominates. The output emitted power signal contains frequency components at DC and at sum/difference frequencies. Of particular importance are the intermodulation distortion products that fall within the desired passband. A significant problem arises if two strong interferers experience third or fifth order nonlinearity and the resulting odd-order IMD products fall within the desired passband. The transfer characteristic of the VCSEL may be described by a power series whose coefficients can be determined through optical measurements. Based on these premises, a technique was developed in which the distortion characteristic of the laser emitter is mitigated by applying compensatory distortion to the signal current energising the device. This approach is simple in concept and has the ability to improve linearisation of the entire optical link. This work represents a significant new objective introduced to the project. The method.has great potential for use in wideband, multicarrier systems, and lends itself to integration into low-cost integrated optical fibre transmitter ICs. An experimental CMOS optical transmitter was developed to evaluate this approach. It comprised three stages: an RF combiner stage, analogue predistortion-linearisation modulator, and a bias current control stage. The RF combiner stage combines the input voltages and converts them to a current signal. It is designed to avoid clipping distortion, and operates at bit rates of up to 2.5Gb/s with each VDSL input. The analogue predistortion circuit imposes a nonlinearity having the inverse transfer characteristic of the directly modulated VCSEL, as shown in Figure 14(a). Figure 14(b) shows the basic predistortion-linearisation circuit.

(a)




(b)

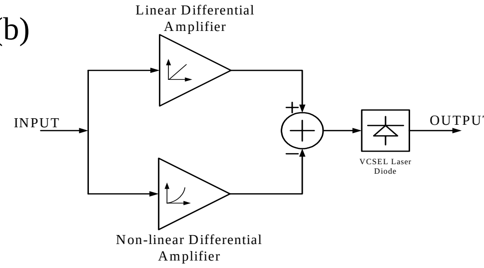



Figure 14 (a) Predistortion compensation method
(b) basic circuit

It consists of two differential amplifiers: a nonlinear differential amplifier, and a linear differential amplifier. The two schematics are identical, but the devices are sized to obtain different transfer characteristics. In conjunction with the RF combiner these act as transconductance amplifiers. When the summed output signal is passed through the VCSEL, distortion components cancel. The combined current signal is modulated over a range of 3mA to 12mA at bit rates of 2.5Gb/s. A bias current of 7.5mA is applied. The system was designed to operate in the frequency range 50 MHz to 1.5GHz; the circuit was implemented using the *austriamicrosystems* (AMS) 0.35µm CMOS technology, with fabrication via Europractice. The device was found to have a maximum bandwidth of 287MHz, but considerably lower gain than expected. However, it was suitable for verifying the principle and for initial assessment.

### 2.7.Enhanced VCSEL Modulator-Driver

Measurements carried out on the experimental VCSEL driver confirmed the validity of the design principle, but actual characteristics of the predistortion amplifier were different from those predicted by device-level simulation based on SPICE MOS Level 3 models. The latest available simulation models were therefore obtained from Berkeley (BSIM3v3.3 [17]). In addition, a methodology based on the use of Volterra Series was developed and applied initially to the analysis of RF mixer structures (see Fig. 15 below) and also the VCSEL driver; from comparison with other approaches and measured results, it has become clear that this gives a much enhanced insight into the behaviour of linear MOS circuits, with much more accurate prediction of stage non-linearities.

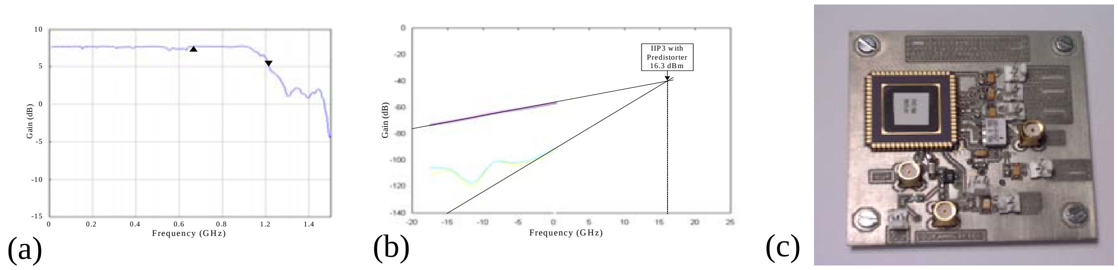



Figure 15(a) Laser driver bandwidth (Honeywell HFE 4080-321) (b) IIP3 response (c) test assembly

This formed a major part of the work carried out and is regarded as an important development in the use of MOS devices for critical mixed-signal applications. A further fabrication phase was commissioned to evaluate an enhanced circuit which embodied design improvements, external control of bias settings, an improved output pad, and better protection against latchup. In addition, a variable-gain linear amplifier was incorporated to allow independent control of signal amplitude within the pre-distortion circuit, to give better control of the distortion characteristic. The opportunity was also taken to develop improved test circuit boards and implement a more advanced control and data acquisition system to facilitate more extensive tests. Figure 15(a) illustrates the response of the CMOS laser driver (variable gain amplifier and predistortion circuit). The driver achieves a bandwidth of 1.21GHz. High frequency fluctuations at 1.35 GHz and 1.46GHz are thought to be due to the network analyser and test assembly (Fig 15(b)). IIP3 performance was determined by applying two signal inputs with the predistortion circuit operating. At the current time the fabricated parts are awaiting final assembly and link test at Essex.

### 2.8.Low-Bounce Adaptive CMOS Buffer for Optical Receiver

A CMOS output buffer has been developed [16] suitable for use in a high speed optical wireless front-end receiver. The buffer operates at bit rates of up to 310Mb/s, and has 20 pF drive capability, but with superior immunity to noise from interconnect and package parasitics compared with conventional approaches. It is implemented in a 0.35µm CMOS process to provide a low power dissipation of 5.73mW, low power/ground bounce, and low output ringing. Measurements on the fabricated device showed >50% reduction of power and ground bounce compared to other reported drivers. It is 30% faster in delay time and has low switching noise.

### 2.9.MOS Mixer/Modulators for Optical Communications

The mixer/modulator is a vital component in modern communication systems, both electro-optical and RF, for frequency up- or down-conversion and other operations; its characteristics largely determine the overall system performance. A mixer/modulator is required to have high linearity to reject distortions which give rise to intermodulation products and other unwanted responses; however, other aspects of performance (conversion gain, bandwidth, SNR) must also be optimised. In this project we have undertaken a detailed investigation of techniques for optimising the performance of devices implemented in CMOS, which has recently become a competitive candidate for RF circuit design, and it is believed the results so far obtained for MOS devices are of considerable novelty. The work has formed an entirely new but complementary objective for the Oakleaf programme

Conventional methods for prediction of distortion in MOS circuits at high operating frequencies fail owing to memory effect. It has previously been shown that Volterra series may be employed for accurate nonlinear distortion analysis in bipolar devices, hitherto the main choice for mixer designs, but owing to the inherent complexity of the method, very few results have been presented for MOS. In this project, a complete procedure has been developed for the analysis of transconductance distortion in key CMOS structures by the method of Volterra series, and detailed calculation steps have been presented. Results obtained agree well with data obtained by simulation using the accepted method of harmonic balance. Further, it has been shown that the use of analogue pre-distortion techniques can achieve mixer/modulators of even higher linearity (described elsewhere). A combination of these approaches is being applied to optimise other MOS mixer structures including the well-known Gilbert Cell. Two novel mixer topologies are under detailed investigation: one is based on cross-coupled differential pairs, with an adjustable current sink controlling the pre-distortion signal which linearises the switching pair. The second is based on a pair of coupled transconductance amplifiers, which are of subtly different dimensions, and generate different distortion components. If complementary signals are applied to the inputs, odd order harmonics and intermodulation distortions can be cancelled and only even order components will appear. The converted signal may drive a double balanced switching stage in which even order distortion components are cancelled. Hence, this topology has the ability to cancel both the odd order and the even order distortion components. For a cross-coupled differential pair, optimisation shows a 2.5 dBm IIP3 improvement. A further improvement is expected from further optimisation of the bias voltage and dimensions. It has been shown how these enhancements may be combined with use of a LCR tuned block, to improve the bandwidth. This work is very new, and it is hoped it will lead to a direct collaboration with an industrial partner; submissions to the scientific press are in preparation.

## 3. Project Plan Review and Research Impact

The project has been successful in achieving its objectives. It foresaw the burgeoning interest in "broadband to the home" technology, and predicted the need for cheap access based on optical fibre to extend its reach, and that fullest possible advantage must be taken of microelectronic device integration. The project produced working prototypes as in proposed, and introduced new design methods for key components including laser drivers, mixers and modulators, in a further step towards possibility of an entire 'photonic system on a chip'. This has attracted interest from Eu project consortia and local industry. The work done is expected to be taken up by collaborators and to influence ISPs' broadband provision strategy.

## 4. Communication of Research Output

Members of the programme presented papers at each of the last three major international conferences on optical communications including a number of invited papers. In excess of 15 conference papers have been presented by programme members on material generated by the project. 2 journal papers have been authored by programme members, and further journal papers are expected to appear. Key publications are documented on the project web-site: http://www-g.eng.cam.ac.uk/mentor/oakleaf

## 5. Expenditure

There were minor adjustments to expected patterns of expenditure. Between November 2003 and March 2004 no researcher was available to carry out the work at Cambridge, and a short extension was granted to the project. Maintenance for an RS appointed in March 2004 was paid for 16 months, while fees came from other sources, leading to underspend in this category. At Essex, only students were used. Overall the project was completed with a net underspend.

## 6. References


1. The Communications Market 2005, Independent market research and data report on current broadband market, http://www.ofcom.org.uk/research/cm/cm05/ , 2005.
2. Jason J. Lepley, Manoj P. Thakur, Ioannis Tsalamanis, Carlos Bock, Cristina Arellano, Josep Prat and Stuart D. Walker, "VDSL Transmission over a Fibre Extended Access Network", Journal of Optical Networking, OSA, Vol. 4, No. 8, July 2005, pp. 517-523
3. J. A. C. Bingham, ADSL, VDSL and Multicarrier Modulation, (Wiley, 2000).
4. M. P. Thakur, T. Quinlan, S. D. Walker, D. M. Holburn, M. C. Parker, C. H. Hum,"Hybrid Network Access Loop for Subcarrier Multiplexed VDSL Transmission", PREP 2002
5. M. Thakur, C.H. Hum, J. J. Lepley, I. Tsalamanis, M. C. Parker, S. D. Walker, "Automatic Cold Start Link Optimization Of Directly Modulated VCSEL Based VDSL Networks" , European Conference on Optical Communications (ECOC 2004)
6. J.J. Lepley, C.H. Hum, M.P. Thakur, M.C. Parker and S.D. Walker, "Super DMT: A concatenated discrete multitone modulation scheme for efficient multiplexing of xDSL signals in Access Networks" , European Conference on Optical Communications (ECOC 2004)
7. M. P. Thakur, I. Tsalamanis, J. J. Lepley and S. D. Walker, "VDSL Transmission over Latin Routed DWDM Optical Access Networks", Proc. OFC / NFOEC 2005 Anaheim, JWA56, March 2005
8. C. Bock, J. Prat, "WDM/TDM PON experiments using the AWG Free Spectral Range Periodicity to transmit Unicast and Multicast Data", OpticsExpress, OSA, Vol. 13, No. 8, April 2005, pp. 2887-2891
9. C. Bock, M.P. Thakur, C. Arellano, J.J. Lepley, S.D. Walker and J. Prat, "Wavelength Independent RSOA-based ONU for FTTH PON Implementation of Switched Ethernet Services", Proc. ECOC 2005, Sept. 2005, Mo4.3.3
10. M.P. Thakur, C. Bock, J.J. Lepley, I. Tsalamanis, C. Arellano, J. Prat and S.D. Walker, "Passive VDSL Transmission over Single Fibre using Reflective Technique at Customer Premises", Proc. ECOC 2005, Sept. 2005, Mo4.3.4
11. C. H. Hum, S. D. Walker, V. A. Lalithambika, Fu-Chuan Lin, D. M. Holburn, M. B. Thakur, T. Quinlan and M. C. Parker, "Optical Access Keying Featuring Low-Power Electronic Adaptive Function" in Proceedings of IEE Photonic Access Technologies Conference, London, U.K., December 2002, pp. 17/1-17/4.
12. Vinod A Lalithambika, Lin, Fu-Chuan, D M Holburn, R J Mears, C H Hum, S D Walker; "Simulation study of BER and signal-to-noise ratio of multichannel optical subcarrier modulated QAM-VDSL signals" in: Optical Transmission, Switching, and Subsystems. Ed. Lam, Cedric F; Fan, Chongcheng; Hanik, Norbert; Oguchi, Kimio. Proceedings of the SPIE, May 2004, Volume 5281, pp. 640-646.
13. Fu-Chuan Lin, Vinod A. Lalithambika, David M. Holburn and Robert J. Mears, "A 2.5Gb/s Low-Power CMOS VCSEL Transmitter with Clipping Distortion Suppression for Analogue Optical Fibre Data Links" in Proceedings of The 5th International Conference on ASIC, Beijing, China, October 2003.
14. Fu-Chuan Lin, Vinod A. Lalithambika, David M. Holburn, Robert J. Mears, Chak H. Hum and Stuart D. Walker, "'A CMOS Analogue Predistortion Circuit for Wideband Optical Fibre Links" in Proceedings of IEEE Canadian Conference on Electrical and Computer Engineering (Special session), Niagara Falls, Canada, May 2004.
15. Fu-Chuan Lin, David M. Holburn, "Linearisation for Analogue Optical Links using Integrated CMOS Predistortion Circuits" in Proceedings of SPIE International Symposium on Microtechnologies for the New Millennium, Sevilla, Spain, May 2005.
16. Fu-Chuan Lin, Vinod A. Lalithambika, David M. Holburn and Robert J. Mears, "A Low-Bounce Adaptive CMOS Output Buffer for 310Mb/s Optical Wireless Receiver" in Proceedings of XVIII Conference on Design of Circuits and Integrated Systems, Ciudad Real, Spain, November 2003.
17. BSIM3 Version 3 Manual, BSIM Research Group, Department of Electrical Engineering and Computer Science, University of California, Berkeley. http://www-device.EECS.Berkeley.EDU/bsim3