Optimum Power Tapping Ratio in WDM Packet-based Access Networks incorporating E-CDMA Control Signalling

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Abstract— **This paper presents a performance study of the electronic code division multiple access based control signalling scheme in a wavelength division multiplexed packet based access network in terms of the required power budget to monitor the electronic code division multiple access control signals in the presence of several sources of noise for error-free transmission of both payload data and electronic code division multiple access based control signals. It is shown that the modulation depth of each signal impacts the amount of required optical tap power. As the modulation depth of the electronic code division multiple access based control signal is increased, the required optical tap power is reduced. However, this increases the bit-error-rate for the payload data. Therefore, there lies a maximum and a minimum of the required tap optical power for the successful recovery of both signals. The lower bound of this range is usually determined by the successful recovery of electronic code division multiple access based control signal while the upper bound is determined by the successful recovery of payload data. The required optical tap power is analysed for different transmission bit rates of the payload data for a distributed star architecture scenario with an optical amplifier at the receiver.**

Keywords- Control signalling, electronic code division multiple access, optimum power tapping ratio, packet networks, wavelength division multiplexing

I. INTRODUCTION

Most of today's data networks are supported using the Internet Protocol (IP) and as the Internet continues to evolve, the data traffic carried by local area networks (LANs) is on the rise. Consequently, future access and LAN architectures should be optimised for IP transport to provide broad bandwidth at affordable cost. Packet based access networks based on high performance Ethernet and/or Multi Protocol Label Switching (MPLS) solutions are being currently investigated for deployment [1]. MPLS can be seen as an extension of the all-Ethernet packet based architecture, where it allows use of Ethernet interfaces but making use of the label-switching paradigm instead of Ethernet switching. The demand to deliver higher bandwidth, rich mix of conventional and new services such as high speed internet access, storage area networking, local area networking and on-demand/broadcast video services such as tele-conference and tele-teaching, file transfer across the computer terminals has increased the inability of conventional copper based Ethernet networks to reliably offer the required peak data rates (~1 Gb/s) and the expected throughputs at an acceptable cost. With the recent standardisation of Gigabit Ethernet technologies, fibre optic links between key network routers or gateways can be deployed to realise reliable high data rate networks for a local/wide area networking applications [2, 3]. Optical networking all the way to the computer desktops have become important in realising fibre-to-the-desktop (FTTD) capabilities combined with wavelength division multiple access (WDMA) as a way of offering cost-effective, reliable and highly efficient network infrastructure for distributed data processing applications.

When an optical access network is implemented, a signalling system within the network that coordinates the traffic among customer terminals is required. Many signalling protocols proposed for these kinds of networks such as carrier sense multiple access, aloha, and token ring are inefficient due to the large propagation delay between the terminals [4]. Ethernet is the most widely used link layer protocol and has the potential to yield a seamless optical network across the different network boundaries, from a wide area network to a local access network, a physical layer signalling mechanism that supports the media access control layer, which is implemented as one of the functions on an Ethernet interface card may be realised at each customer terminal to yield high throughput at low cost. A few of the proposed techniques for control packet signalling are optical subcarrier multiplexed (SCM) signalling [5], dedicated wavelength channel signalling [6] and optical code division multiplexed (OCDM) signalling [7]. SCM signalling technique adds complexity at each network terminal in the forms of active higher bandwidth optoelectronic components at the modulation and detection. Moreover, increasing the SCM signals will lead to nonlinear effects in the RF and optical domains. The use of multiple RF subcarriers limits the performance due to dispersion, optical beat interference (OBI) and the scalability while the performance of the SCM signalling technique is also reduced by the analog subcarrier detection circuits. In the dedicated wavelength channel signalling, header of a packet is carried on a dedicated wavelength channel. This scheme increases the throughput of the network since most of the wavelength channels are occupied with the payload data of the packet. However, due to the fibre dispersion, the synchronisation between the header and payload of a packet may be lost. Therefore, realignment of the payload and header at each network terminal is required that could make the system more complex. Moreover, the requirement of an additional wavelength channel to carry the header of a packet is not effective in the cost sensitive access networks. OCDM signalling has been demonstrated using bit level coding and header processing. Moreover, packet routing and switching are also performed using this technique. Although high speed photonic packet routing based on OCDM has been experimentally demonstrated, it is too difficult and costly to perform low-level functions in access networks.

II. CONTROL PACKET SIGNALLING USING ELECTRONIC CODE DIVISION MULTIPLE ACCESS

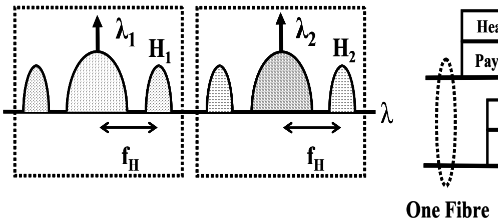

Fig. 1: E-CDMA control packet signalling.

A control packet signalling technique based on electronic code division multiple access (E-CDMA) has been developed for the WDM packet based access networks [8, 9]. In the E-CDMA signalling technique, each wavelength channel in the network is assigned a unique electronic code allowing a particular wavelength channel to be identified anywhere in its path by its predefined code. The header of the packet is electronically multiplexed with the electronic code, which is higher in bit rate to produce a direct sequence spread spectrum (DS-SS) signal. The resultant DS-SS signal, which is termed as E-CDMA hereon, is then modulated onto a RF carrier frequency, whereby the RF carrier frequency is chosen to be outside the bandwidth of the baseband payload data of the packet. As each wavelength channel uses a unique electronic code, the RF carrier frequency is common to all WDM channels as can be seen from Fig. 1. This enables the use one standard E-CDMA access control interface card at all customer network terminals. The up-converted E-CDMA coded header and payload of a packet transmitted within the same time slot. The performance limitations that arise in SCM signalling due to the RF mixing of the multiple RF subcarriers, RF bandwidth constraints on the photonic components, OBI, dispersion, and scalability problems are reduced in E-CDMA signalling technique. Moreover, a wavelength demultiplexer and multiple WDM interfaces are not required at the intermediate nodes to process the E-CDMA control signals. The bandwidth requirements for E-CDMA signalling technique is lower than that required for the SCM signalling technique since one RF carrier is used to carry all E-CDMA control signals. E-CDMA control signals are carried in the same wavelength channel as the payload data signals and therefore the cost savings are high compared to the dedicated wavelength channel signalling mechanism. Each network terminal is equipped with the low-cost E-CDMA access control interface card and these E-CDMA access control interface cards may be integrated with the Gigabit Ethernet optical transceivers allowing an easier upgrade path for an existing optical access network infrastructure. The requirement for large number of external electronics can be minimised using this technique and enables the use of an existing technology with reduced use of additional custom designed RF and optical interfaces. This E-CDMA control packet signalling technique is capable of being digitally implemented [10, 11] to ease the hardware complexity, bandwidth constraints and reduced nonlinearity to get better CNR for error-free transmission. Moreover, it has been shown that the use E-CDMA could vastly reduce the performance limitations induced by fibre dispersion [12] and OBI [13].

III. THEORETICAL ANALYSIS OF OPTIMUM POWER TAPPING RATIO IN DISTRIBUTED PASSIVE STAR ARCHITECTURE

To ensure successful operation of the network, the E-CDMA control signals are monitored by tapping a percentage

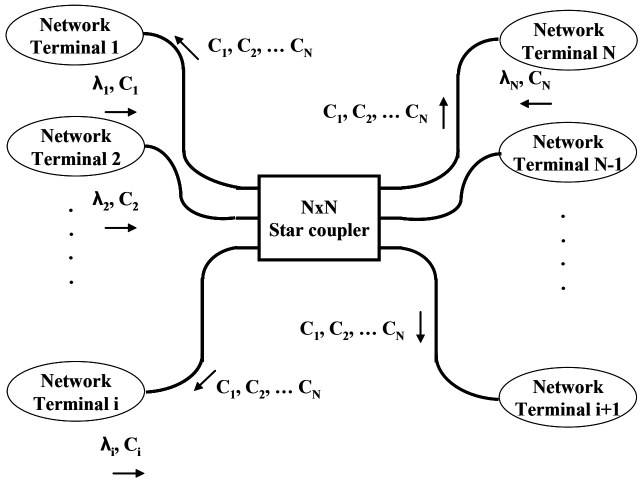

Fig. 2: Distributed WDM star network incorporating E-CDMA signalling.

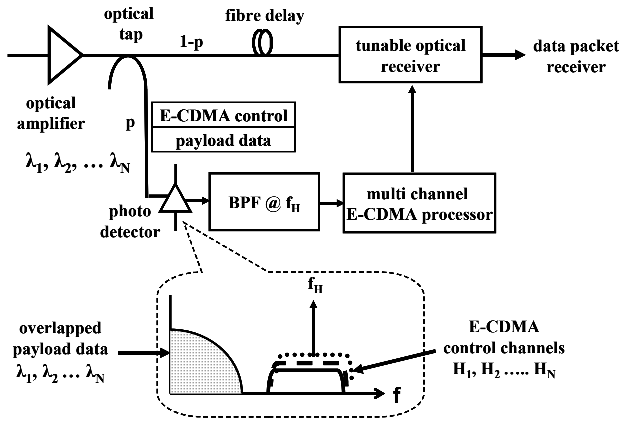

Fig. 3: Receiver architecture of the network terminal.

of the optical power at each network terminal for the recovery of an E-CDMA control signal from each wavelength channel. In this section, the scalability of the E-CDMA control signalling mechanism is analytically investigated to evaluate the optimum optical power tapping ratio for error-free recovery of both E-CDMA control signal and baseband payload data signal. For the scalability analysis, a distributed WDM star network incorporating E-CDMA control signalling is considered as shown in Fig. 2. However, other architectures such as ring networks can also be considered. This WDM star network uses TT-FR architecture, whereby a fixed wavelength channel is allocated to each network terminal for the reception of the data from other network terminals. Fig. 3 shows the receiver structure of the network terminal. Two arms are employed in the receiver, whereby the control arm taps p fraction of the optical power of the signals that enter the network terminal. The remaining (1-p) fraction of the optical power goes to the data arm for the recovery of the baseband payload data signals. To ensure the successful operation of the network, the error-free transmissions of both the E-CDMA control signal and baseband payload data signals (taken to be $BER < 10^{-9}$) are equally important. We derive the analytical expression of the BER of both the E-CDMA control signal and the baseband payload data signal. Several sources of noise are considered for both E-CDMA control data and payload data such as shot noise, RIN noise, thermal noise, signal-spontaneous beat noise, and spontaneous- spontaneous beat noise.

The header data is defined as

$$d_k(t) = \sum_{j=-\infty}^{+\infty} d_j^k P_T(t - jT_d)$$

which takes on values [-1, 1] and $p_T(.)$ is a rectangular NRZ waveform of T_d second duration. The assigned spreading code for a wavelength channel can be written as [14]

$$c_k(t) = \sum_{j=-\infty}^{+\infty} c_j^k P_{T_C}(t - jT_C)$$

Here, the spreading code consists of a periodic sequence of rectangular chips taking on values [-1, 1] each T_C second duration. After spreading the header data, the resulting E-CDMA control signal is then is BPSK modulated onto an RF carrier frequency and can thus be expressed as

$$s_k(t) = \sum_{k=1}^{k} d_k(t - \tau_k)c(t - \tau_k)\cos(\omega_C t + \theta_k)$$

where ω_C is the RF carrier, θ_k is the phase of the RF carrier. The resulting RF upconverted E-CDMA control signal is combined with the baseband payload data. The baseband payload data can be written as

$$b_k(t) = \sum_{j=-\infty}^{+\infty} b_j^k P_{T_b}(t - jT_b)$$

Here, b_j^k takes values [0, 1] and T_b is the bit interval for the data. The baseband payload data and the RF upconverted E-CDMA control signals are combined with a ratio of $b_k(t) : s_k(t) = m : 1$. The composite signals are then modulated onto a wavelength channel for the transmission. The instantaneous optical power of the transmitted signals is given as

$$P(t) = P_o\left[\begin{array}{l} 1 + \sum_{k=1}^{k} d_k(t - \tau_k)c(t - \tau_k)\cos(\omega_C t + \theta_k) \\ + m\sum_{j=-\infty}^{+\infty} b_j^k P_{T_b}(t - jT_b) \end{array}\right]$$

Here, the average optical power can be written as

$$P_{av} = P_O\left(1 + \frac{m}{2}\right)$$

At the receiver, p fraction of the total optical power is tapped and detected using a PD. The resulting photocurrent at the BPF output can be given as

$$i_C(t) = pR_P P_r \sum_{k=1}^{k} d_k(t - \tau_k)c(t - \tau_k)\cos(\omega_C t + \theta_k)$$

where $P_r = \dfrac{L_T P_{av}}{\left(1 + \dfrac{m}{2}\right)}$ is the received optical power.

The photocurrent includes the contributions of the desired E-CDMA control signal and interfering signals from other terminals. After despreading, the wideband electronically coded signal collapses into a narrowband signal, which is received at the LPF output of a demodulator in the multi-channel E-CDMA processor. The MAI power at the output of the LPF can be expressed as [15]

$$I = \frac{1}{2}(N - 1)(pG_A R_P L_T P_{av})^2 G_P^{-1}$$

whereby the processing gain is $G_P = \dfrac{T}{T_C}$. The power all E-CDMA control signals is assumed equal. Considering that RIN noise (N_{RIN}), thermal noise, ($N_{thermal}$), and shot noise (N_{shot}), components are present at the demodulator input, and that all nodes transmit concurrently, the respective noise variance at the E-CDMA decoder input can be expressed as

$$N_{RIN} = (N - 1)RIN\,(pG_A R_P L_T P_{av})^2 B_w$$

$$N_{thermal} = einc^2 B_w$$

$$N_{shot} = 2epNR_P\left(G_A L_T P_{av} + P_n(G_A - 1)B_f\right)B_w$$

where $N, RIN, R_P, B_w, einc, T, R_L, e, G_A, B_f, P_n$ are number of channels, power spectral density (PSD) of the relative intensity noise, responsivity of the photodetector, noise bandwidth of the control arm, equivalent noise input current, noise temperature, load resistance, electron charge, gain of the optical amplifier, bandwidth of the optical filter after the optical amplifier, and spontaneous emission factor of the optical amplifier respectively. Here, the shot noise and RIN noise are considered to be in the worst case whereby all wavelength channels are received at a terminal simultaneously.

Moreover, as an optical amplifier is placed in the front end of the receiver, the spontaneous emission present appears as noise in its output. This spontaneous noise field beats against the signals and against itself in the photodetector giving rise to the noise components referred to as the signal-spontaneous beat noise and spontaneous-spontaneous beat noise respectively. The variances of these noise currents are given as

$$N_{sig-sp} = 4pNR_P^2 G_A P_r P_n (G_A - 1)B_w$$

$$N_{sp-sp} = 2pR_P^2[P_n(G_A - 1)]^2(2B_f - B_w)B_w$$

Here, $P_n = n_{sp}hf_c$, whereby h and f_c are Planck's constant and optical frequency respectively.

The parameter $L_T = L_f L_{SC}$ is the total loss between the end-end terminals whereby L_f is the loss through fibre. The star coupler (SC) splitting loss is given by

$$L_{SC} = 10\log(2N - 2)$$

As E-CDMA control signal is BPSK encoded, and S being the E-CDMA control signal power, the signal-to-noise ratio (SNR) and BER can be calculated using

$$SNR = \frac{S}{N_{RIN} + N_{thermal} + N_{shot} + I + N_{sig-sp} + N_{sp-sp}}$$

$$BER = \frac{1}{2} erfc \sqrt{\frac{SNR}{2}}$$

Similarly, the BER for the baseband payload data can also be calculated. For the baseband data signal, the photocurrent in the baseband payload data-arm can be expressed as

$$i_d(t) = R_P(1-p)P_{rd}\left[1 + m\sum_{j=-\infty}^{+\infty} b_j^k P_{T_b}(t - jT_b)\right]$$

where P_{rd} is the received power at the baseband payload data arm. In the baseband payload data-arm, shot noise variances differ for space σ_{d0}^2 and mark σ_{d1}^2.

$$\sigma_{di}^2 = 2e\left[R_P(1-p)G_A P_{rd}(1+im)\right]B_d$$

for i =0 and 1 respectively. Here, we represent the total noise variances as.

$$N_{shot} = \sigma_{d0}^2 + \sigma_{d1}^2 + 2(1-p)eR_P P_n (G_A - 1) B_{f-data} B_d$$

Like wise, the remaining noise components can be expressed as

$$N_{RIN-data} = RIN\left((1-p)R_P L_{TD} G_A P_{av}\right)^2 B_d$$

$$N_{thermal-data} = einc_d^2 B_d$$

where B_d is the bandwidth of baseband payload data.

The variances of the noise currents of signal-spontaneous beat noise and spontaneous-spontaneous beat noise are given as

$$N_{sig-sp-data} = 4(1-p)R_P^2 G_A P_r P_n (G_A - 1) B_d$$

$$N_{sp-sp-data} = 2(1-p)R_P^2\left[P_n(G_A - 1)\right]^2 (2B_{f-data} - B_d) B_d$$

$L_{TD} = L_f L_{SC} L_{of}$ is the total loss incurred by the baseband payload data signal, with L_{of} representing the loss in the tunable optical filter.

The equivalent input noise current for the baseband payload data depends on the bandwidth of the baseband payload data signal and therefore can be calculated as

$$einc_d = \sqrt{einc^2 \times \frac{B_d}{B_W}}$$

$$Total\ Noise_{data} = N_{shot-data} + N_{thermal-data} + N_{RIN-data} + N_{sig-sp-data} + N_{sp-sp-data}$$

Using a zero-mean gaussian model for the above noise components, and S_{data} being the data signal power, the *BER* for the data signal is given by

$$SNR_{data} = \frac{S_{data}}{Total\ Noise_{data}}$$

$$BER_{data} = \frac{1}{2} erfc(SNR_{data})$$

Parameter	Value	Units
Rp	0.85	A/W
P_{av}	-3	dBm
G_p	10000	---
B_d	20	Gb/s
B_w	500	Mb/s
$einc_{control}$	2.5 x 10^{-12}	A/√Hz
L_{of}	3	dB
RIN	-150	dB/Hz
Fibre distance	10	Km
G_A	10	dB
N_{SP}	2	--
B_f	2.5	THz
B_{f-data}	100	GHz

Table 1: Parameters and the values used for the analysis of the optimum power budget for the E-CDMA control signal.

Using the above theoretical analysis and appropriate parameters, the performance limitations for the successful recovery of baseband payload data and E-CDMA control signals are analysed. The values chosen for the analysis are given in Table 1.

IV. Results and Discussions

Using the above parameters shown in Table 1, with the modulation ratio $m = 2$ and tap fraction $p = 0.10$, Fig. 4 plots the *SNR* of the E-CDMA control signal against varying number of SC splits or network terminals. Results show that thermal noise is the least dominant noise component. Spontaneous-spontaneous beat noise, shot noise, and RIN noise are more

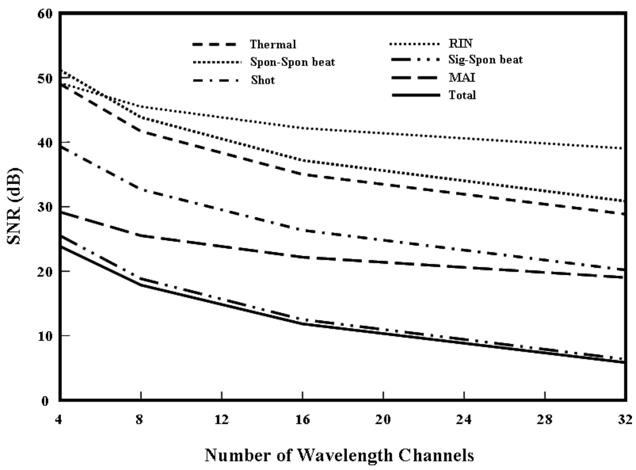

Fig. 4: Signal-to-noise ratio values for limiting noise parameters against the number of network terminals.

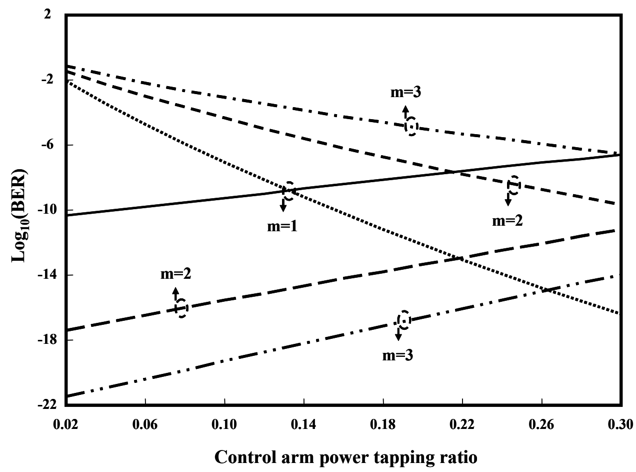

Fig. 5: Control arm power tapping ratios for various modulation depth of the signals for SC splits of 16.

dominant than the thermal noise. As expected, the dominant factors in the total noise are contributed by signal-spontaneous beat noise and MAI. Shot noise also becomes dominant for larger number of wavelength channels. As the gain of the optical amplifier increases more than 10 dB, spontaneous-spontaneous beat noise becomes larger as well. Here, RIN noise is the least dominant noise. Fig. 5 shows the *BER* curves for both signals as a function of control arm power tapping ratio, p, for three values of modulation ratios and for a SC split of 16. As expected, the BER of the E-CDMA control signal decreases with increasing tapping ratio and decreasing m. For lower values of m, lower amount of tapped optical power is adequate. However, the *BER* of the payload data signal increases with increasing tapping ratio and decreasing m. Observe that for every value of m, the tapping ratio is bounded at the minimum to ensure error-free recovery of the E-CDMA control signal, and at the maximum to ensure error-free recovery of the payload data signal. For example, to achieve a BER $< 10^{-9}$, the tapping ratio must be bounded between 11% and 13% for $m = 1$. Therefore, it is seen that the modulation depth of each signal heavily impacts the required tapping ratio for the error-free recovery of signals. Fig. 6 shows the *BER* curves for both signals as a function of control arm power tapping ratio. Here, the transmission bit rate of the payload data signal is varied while that of the E-CDMA control signal is kept constant at 500 Mb/s with $m = 1$. Observe that the *BER* for the data signal increases with increasing bit rate, attributed to

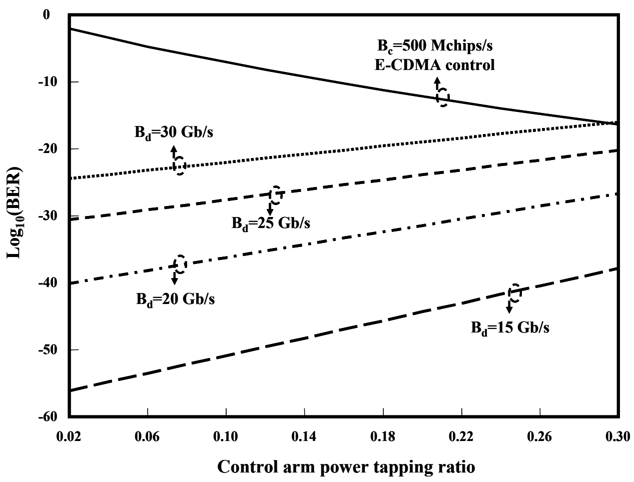

Fig. 6: Control arm power tapping ratios against varying data bandwidth for the SC split of 16 and m=1.

the increased noise bandwidth of the payload data. However, observe that even for high data rates upto 10 Gb/s and relatively high power tapping ratios, error free transmission of the payload data and E-CDMA control signals can be obtained. For all payload data rates shown in Fig. 6, a minimum power tapping ratio of 14% required. As the transmission bit rate of the payload data is decreased, the range increases.

V. CONCLUSIONS

A theoretical analysis to study the power tapping ratio in a WDM packet network that uses E-CDMA signalling mechanism is presented. The results show that the ratio depends on modulation depth and payload data rate. The lower bound is determined by the recovery of E-CDMA signal while the upper bound is determined by the recovery of payload data.

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