IP Transmission Over OCDMA-LAN

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Abstract—**This paper proposes a novel Internet protocol (IP) traffic transmission over multiple array (*M-ary*) frequency shift keying optical code-division multiple-access (FSK-OCDMA) local area network (LAN). The transceiver also enjoys the co-channel interference canceller. The network performance has been analyzed and compared with common incoherent pulse-position modulation (PPM). The results indicate that this architecture is very power efficient and enhances the network capacity. It is shown that for a maximum bit-rate, the network performance can be improved by reducing the channel utilization. Since each IP packet is buffered only at the edge of this network, the buffer delay is considerably reduced.**

Index Terms—**Frequency shift keying, IP traffic, LAN, multiple access interference (MAI), optical CDMA, prime codes**

I. INTRODUCTION

THE Internet protocol (IP) has been the dominant protocol to deliver the recent multimedia-on-demand services and still expected for the future. Accordingly, to support huge number of users demanding high bit-rate services, an expansion in the network capacity leading to the higher data traffic is required. Although the IP routing, operates electrically in the network layer, cannot be processed at a speed matched the huge transmission speed offered by the fiber optic, it thus became the main challenge in the optical networking. Multiprotocol label switching (MPLS) can be a solution [1] since at the intermediate nodes a packet is forwarded only according to its label. Since network layer label analysis is avoided, significant processing time is saved at each hop. The end-to-end delay can also be significantly reduced because IP routing is only needed in the edge routers. Although MPLS partially relieves the IP routing, the electrical routing scheme will still become a bottleneck as IP traffic increases [2]. Optical packet switching (OPS) can be another solution by use of pure optical signal processing. There are though many difficulties in contention resolution [3] and optical buffers [4] that make OPS still an immature technology.

To mitigate the problem of traffic growth and need for enhanced multiple user access to the network resources, optical code-division multiple-access (OCDMA) has shown a lot of potentials in optical networking [5]. This technique allows multiple concurrent users to share the same medium at the same time and wavelength. To compare with time-division multiple-access (TDMA), OCDMA supports bursty and asynchronous networks traffic, i.e. IP traffic nature, without the need for expensive and precise electronic circuits resulting in simplified network functionality and management. It is attractive for its dynamic capacity and flexible bandwidth management, supporting random access protocols and superior security [6].

Coherent time spreading OCDMA has recently drawn a lot of attention because of its superior performance over incoherent schemes [7]. In the incoherent schemes such as on-off keying modulation and power detection, the most severe issues are the coherent signal interferences and the incoherent multiple access interference (MAI). In addition, the intensity-modulated incoherent structures are vulnerable in terms of security, which could easily be broken by simple power detection, even without any knowledge of the code [8]. On the other hand, in the spectral amplitude coding (SAC) OCDMA, the performance is degraded due to the use of a broadband source that generates a noise referred to as phase-induced intensity noise (PIIN) [9]. This becomes the major factor of performance degradation in SAC as PIIN is proportional to the generated current in photo-detectors.

In the FSK-OCDMA, $\log_2^M$ encoded bits of data (symbol) are assigned to M wavelengths for all users as a result of *M-ary* source coding. Therefore, this brings the network higher spectral efficiency (fewer set of wavelengths used) with no wavelength assignment [10].

Since the number of slots in a data frame is independent of the number of symbols, the bit-rate of FSK does not decrease as the number of symbols increases. When the number of slots in a frame is γ (i.e. corresponds to the repetition ratio of the tunable laser), the bit-rate of *M-ary* FSK becomes M/γ ($\gamma < M$) times higher than that of *M-ary* PPM [11]. It has been discussed that, the probability of having interference for *M-ary* FSK is $1/M\gamma$, while the corresponding probability for *M-ary* PPM is $1/M$.

In terms of optical signature sequences, double-padded modified prime code (DPMPC) has been utilized. DPMPC has been extensively introduced and applied to different OCDMA architectures such as incoherent pulse position modulation (PPM) and overlapping PPM [12], coherent OCDMA [13], FSK-OCDMA [11] and also in conjunction with polarization shift keying [14]. DPMPC has P groups, each of which has P code sequences, thus the total number of available codes is P^2 where P is a prime number. The code-length and code-weight (number of ones) of each code sequence are P^2+2P and $P+2$ respectively. The in-phase auto- and cross-correlation functions, C_{mn} for any pair of codes m and n is given by:

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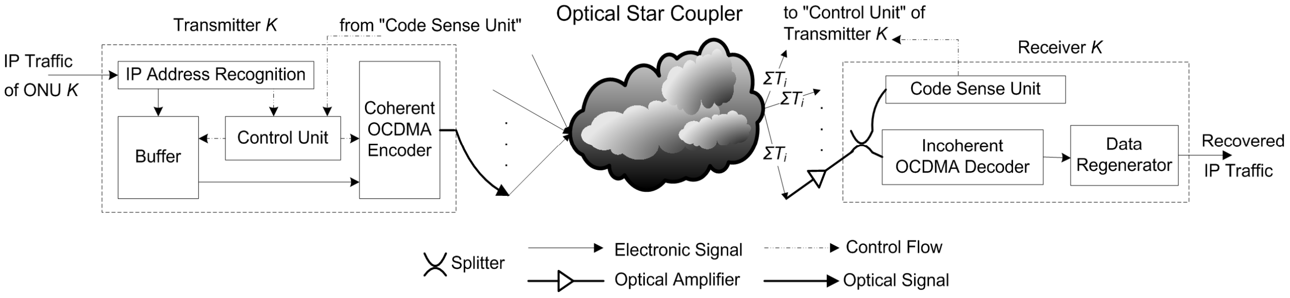

Fig. 1. Configuration of proposed IP transmission over OCDMA network

$$C_{mn} = \begin{cases} P+2, & \text{if } m = n \\ 0, & \text{if } m \neq n,\ m \text{ and } n \text{ share the same group} \\ 1, & \text{if } m \neq n,\ m \text{ and } n \text{ share the different groups} \end{cases} \quad (1)$$

where $m,n \in \left\{1,\dots,P^2\right\}$.

In our analysis, the coherent FSK with incoherent demodulation with IP transmission has been introduced. The hybrid scheme takes advantages of both noise immunity of coherent modulation and simplicity of incoherent demodulation. It is shown that the average number of active users in the network changes when different channel utilizations are applied. Channel utilization is a parameter relative to the assigned users' bit-rate which will be defined later. Since the performance of OCDMA network is a function of the number of active users, the channel utilization will have a significant effect on the performance.

The rest of the paper is organized as follows. The network architecture and IP transmission is described in section II followed by the IP traffic analysis in section III. The results are discussed in section IV and finally the study is concluded.

II. IP TRAFFIC OVER FSK-OCDMA

The architecture of the IP traffic transmission in the OCDMA network is shown in Fig. 1. At the transmitter node, the destination of each incoming IP packet is recognized, the packet recognition can be performed by address correlation process and then the packet is saved into the buffer. The buffer is divided into K first-in-first-out (FIFO) subparts, referred to the total number of users. The IP packets that are destined for different receivers are stored in different subparts accordingly. When IP packets are to be transmitted to the same receiver, they are saved in the allocated FIFO subpart in order. It is important to note that the purpose of storing IP packets separately according to their destination address is to send all the IP packets to the same receiver at one time and at a high speed. Thus, the optical encoder is adjusted for number of packets belonged to the same user rather than being tuned for every incoming IP packet individually. As a result, the encoder adjusting time requirement is significantly reduced. The adjustment refers to the tunable address code (i.e. DPMPC) generator. The control unit is responsible to record the total traffic of each subpart. When the total traffic is greater than a certain value i.e. a threshold, the control unit tries to send the packets to the assigned address. Before sending, the optical encoder has to be adjusted according to the desired address sequence i.e. DPMPC generator in Fig. 2a. When the threshold is large, the buffer delay becomes predominant. However, due to the higher transmission speed, proper selection of a threshold value makes this delay acceptable. The star coupler mixes all the outgoing optical signals and this superimposed signal is amplified and transmitted to the receivers of all users. Due to the broadcast nature of OCDMA communication, the processing is performed in code domain and every subscriber is recognized by its assigned code, the scheme can be considered as self-routing.

At the receiver, the optical decoder retrieves only the intended signal and regenerates the original data stream. When two (or more) transmitters send signals to the same receiver at the same time, a collision may occur. In order to prevent the collision, a code sense unit is designed to sense whether others are sending data to the same address. In fact, the sense unit can be a correlator to recognize the address sequence configured with the code by which the intended user should be checked. In the meantime, code sense unit is also in contact with control unit both to check whether the optical encoder is adjusted correctly to the desired address code and to prioritize the users to avoid collision.

In this network, owing to the use of coherent OCDMA technique, not only is fiber bandwidth utilized efficiently, but also IP routing is automatically performed (i.e. self-routing). Because each IP packet is buffered only twice at the edge of the OCDMA network, the same as in an MPLS network [15], the buffer delay is significantly reduced as compared with the traditional routing where the packets are buffered at every hops.

Fig. 2 illustrates details of the FSK-OCDMA optical encoder and decoder blocks as introduced in Fig. 1. The *M-ary* FSK allocates M symbols to the corresponding M wavelengths in a data frame rather than the slot positions as in PPM. When the number of symbols (i.e. M) is constant and the repetition ratio γ becomes smaller, i.e. γ corresponds to the number of slots between two subsequent wavelengths by a tunable laser, the bit-rate becomes higher while the channel interference increases [11].

At the FSK modulator in the transmitter shown in Fig. 2a, the data frame consists of γ slots and data (symbols) is allocated into one of the slots. When γ is larger than one, first slot is selected for data position among γ slots in the frame. The subsequent symbols corresponding to its frequency are placed on the same slot position in the following frames. The data is then sent to the tunable laser diode as shown in Fig. 2a.

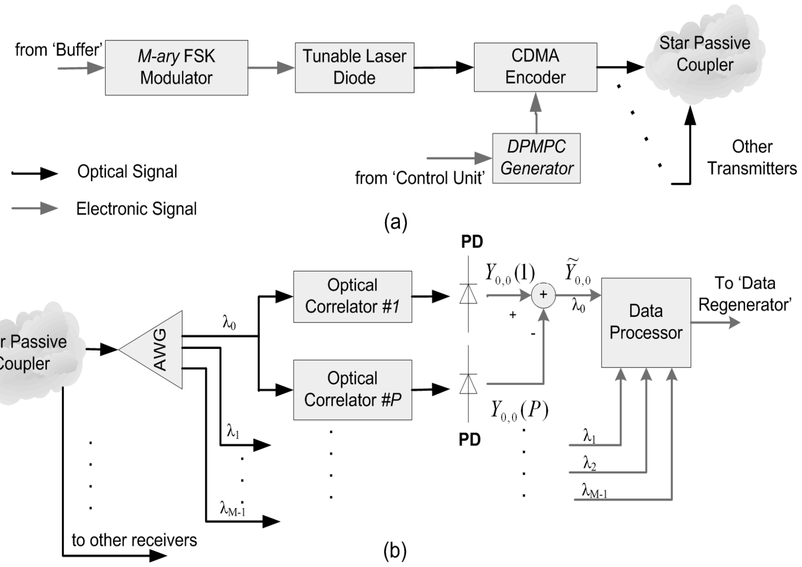

Fig. 2. Inside FSK-OCDMA en/decoder blocks (a) transmitter and (b) receiver with MAI cancellation architectures

The tunable laser emits the certain wavelength corresponding to the symbols at the certain chip positions in a slot derived from the FSK modulator. Note that the other wavelengths are not emitted. The optical pulse is then time spread in the multiple chip positions by the aid of optical tapped-delay lines (OTDL) corresponding to '1s' of the spreading code in the CDMA encoder. Then, the intended user's signal is broadcasted together with the other users through the passive star coupler over the network.

At the receiver shown in Fig. 2b, the received signal is divided into M wavelengths by the arrayed-waveguide grating (AWG). Each wavelength is split into two parts via 1×2 lossless beam splitter passing through the optical correlators in main (upper - co_1) and reference (lower - co_P) branches. The AWG is assumed not to cause any interference between adjacent wavelengths. For example, we allocate the 1st DPMPC code sequence to the intended user (u_1) and use the P^{th} DPMPC code sequence as the reference signal reserved at the OTDL correlator co_P . Therefore, the received signal is correlated both with the first code sequence in the main branch to extract the 'data + interference + noise' and with the P^{th} code sequence in the reference branch to extract 'interference + noise'. Now as shown in Fig. 2b, the data is obtained by subtracting two signals from both branches and accordingly the MAI and noise are cancelled out at each wavelength [11, 12]. Hence, only one reference code is used to cancel the interference for all users. It indicates the total number of subscribers increased to P^2-1 as compared to the PPM structure in which the number of references is P i.e. total number of users is P^2-P [12]. This implies that the receiver operates faster and more power efficient because it has to compare the received signal with only one reference rather than P, thus the receiver structure becomes also simpler accordingly. Finally, the outputs of co_1 and co_P for wavelength λ_m in slot v, denoted as $Y_{m,v}(1), Y_{m,v}(P), m\in\{0,...,M-1\}, v\in\{0,...,\gamma-1\}$ respectively, are converted from optical to electrical signals through the photo-detectors, as in Fig. 2b. After the MAI cancellation per wavelength, the data is extracted through the electric currents in the data processor unit to clarify the symbols with the maximum likelihood receiver and then the corresponding data is obtained and transferred to the data regenerator unit for further IP processing.

III. ANALYSIS OF IP TRANSMISSION OVER OCDMA-LAN

The bit-error rate (BER) for the proposed FSK scheme with the MAI canceller is derived using DPMPC as extensively discussed in [11]. It is assumed that the input/output characteristic of the photo-detectors follows the Poisson process, i.e. the shot-noise is taken into account. Since the reference signal has only the P^{th} sequence (reserved at the receiver, i.e. there is no reference signal or channel) multiplied by the received signal, the data components of reference signal become *zero* due to further spreading. Also, since all users in the same group receive an equal amount of MAI from the users of other groups and no interference from the users from the same group, see (1), the interference signal of u_1 equals the interference signal of P. It is assumed that u_1 transmits the optical pulse of λ_0 at the first slot in a data frame.

Since the DPMPC sequences are employed as signature codes and considering number of interfering users in each group based on its correlation properties and using Gaussian probability distribution functions based on the number of interfering users and interference estimation, the final bit-error probability (P_b) is derived as [11]:

$$P_b \le \frac{M}{2}\sum_{r=r_{\min}}^{r_{\max}}\sum_{l_{0,0}=0}^{K-r}\sum_{l_{1,0}=0}^{K-r-l_{0,0}}\binom{K-r-l_{0,0}}{l_{1,0}}\times\left(\frac{1}{\gamma.M}\right)^{l_{1,0}}\times\left(1-\frac{1}{\gamma.M}\right)^{K-r-l_{0,0}-l_{1,0}}$$
$$\times\exp\left\{-\frac{\rho}{2}.\frac{Q.(P+2)}{2}\right\}\times\binom{K-r}{l_{0,0}}\times\left(\frac{1}{\gamma.M}\right)^{l_{0,0}}\times\left(1-\frac{1}{\gamma.M}\right)^{K-r-l_{0,0}}$$
$$\times\binom{P^2-2P+1}{K-r}\times\binom{P-2}{r-1}\Big/\binom{P^2-P-1}{K-1} \qquad (2)$$

where r is the number of interfering users sharing the same

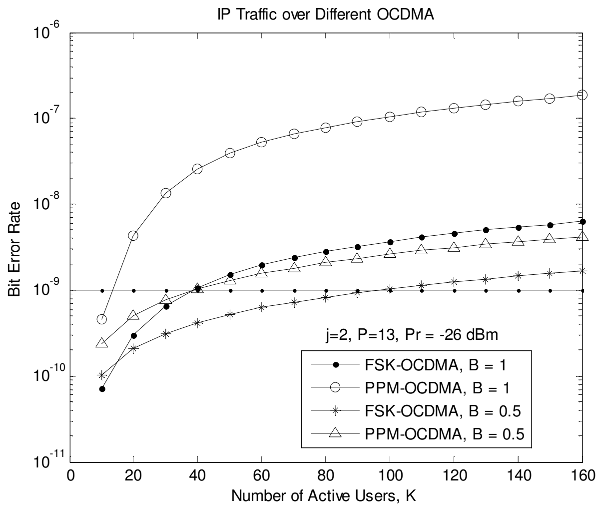

Fig. 3. BER of IP traffic over PPM- and FSK-OCDMA against number of active users, *K*

group and $r \in \{r_{\min},\ldots,r_{\max}\}$, $r_{\max} = \min(K, P-1)$ and $r_{\min} = \max\left(1, K-(P-1)^2\right)$. Here *K* refers to the number of simultaneous active users. $l_{m,v}$ is the number of users who are in groups other than the first group and have a pulse in the v^{th} slot with wavelength λ_m.

Taking the fiber attenuation coefficient of *α* into account, the average received photon count per pulse (*Q*) can be expressed as [12]:

$$Q = \frac{\eta\ P_w}{hf}.\frac{e^{-\alpha L}}{P+2} \approx \mu.\frac{\ln M}{P+2} \qquad (3)$$

where $P_r = \xi.P_w e^{-\alpha L}$ is the received power to the detector, P_w is the transmitted peak power per symbol, η is the quantum efficiency of the photo-detectors, *h* is the Planck's constant, *f* is the optical frequency, *L* is the fiber-length, and *μ* ($\mu = P_r/(h.f.\ln M)$) is the average number of photons per pulse (photons/nat). *ρ* in (2) is the parameter minimizing the interference that equals [11]:

$$\rho = \frac{P+2}{P+2+l_{0,0}+l_{1,0}} \qquad (4)$$

On the other hand, when the bursty IP traffic is implemented to the OCDMA concept, to obtain the acceptable performance without overload, the designed transmission rate for each user should be larger than the average traffic arrival rate. Hence each code channel cannot be fully utilized. It is easy to see that the average number of active users in the network changes when different channel utilizations are applied. Since the performance of an OCDMA network is a function of the number of active users, the channel utilization will have a significant effect on the network performance. For this impact analysis, all users are assumed to have the same channel utilization in the network as defined by:

$$B = \frac{Average\ \ Output\ \ Bitrate}{Maximum\ \ Transmission\ \ Bitrate} \qquad (5)$$

Taking into account that the *zero* and *one* data bits are equiprobable, then the probability of each transmitted bit is $1/2$. Since the users are sending data independently, so the distribution of *K* as a number of active users is K/U where *U* is the total number of users accommodated in the network. Consequently, the probability that *K* users are active ($P_{ac.}$) equals the probability of a transmitted data-bit times the probability of users involved in the transmission times the channel utilization. This can be expressed as:

$$P_{ac.} = \frac{1}{2} \times \frac{K}{U} \times B \qquad (6)$$

Since user activity (sending IP packet) has the binomial behavior [16], the active users among all users can be treated as a binomial distribution. Thus, the PDF of *K* active users are sending IP packet is obtained by:

$$P_{IP}(K) = \binom{U}{K} P_{ac.}^{K} (1 - P_{ac.})^{U-K} \qquad (7)$$

Accordingly, the total probability of error function of number of active users *K*, $P_T(K)$ denoting BER, can be expressed by the decoder probability of error (P_b) times probability of error stating the *K* active users (P_{IP}). This is derived by:

$$P_T(K) = \sum_{k=1}^{K} P_{IP}(k).P_b(k) \qquad (8)$$

Assume that the average IP packet length is *w* bits, the packet-error rate (PER) of the IP traffic over this OCDMA network is then obtained by:

$$PER = 1 - (1 - P_T(K))^{w} \qquad (9)$$

IV. DISCUSSION OF RESULTS

The parameters used for the simulation are listed in Table I. For spreading code, DPMPC with *P*=13 is employed that makes the code-length and total number of users 195 and 168 respectively. The repetition ratio (*γ*), shown by *j* in all graphs, has been considered as 2, obviously by increasing the repetition ratio the performance will be enhanced due to the MAI reduction.

Fig. 3 shows the BER comparison between PPM and FSK schemes against the number of users, *K*. The analysis for PPM-OCDMA can be found in [12] using similar coding and MAI cancellation technique. It is obvious that the performance degrades when the MAI increases by growing the number of users. The received power (P_r) is set to -26dBm in this analysis. It is apparent that the FSK outperforms PPM in that the repetition ratio and *M-ary* signaling mitigate the interference. To compare with [16], the results explain the architecture's power efficiency. As demonstrated in Fig. 3, when the channel utilization is moderate, i.e. *B*= 0.5, the FSK network is able to accommodate 100 active users while PPM supports only 40 users maintaining $BER = 10^{-9}$. In the worst case i.e. B=1, the BER degrades severely. The FSK network though tolerates 40 users at $BER = 10^{-9}$ while only 14 users are accommodated by PPM scheme. It is also apparent that FSK in the worst case (i.e. *B*=1) accommodate the same number as the PPM does when the channel utilization is 0.5.

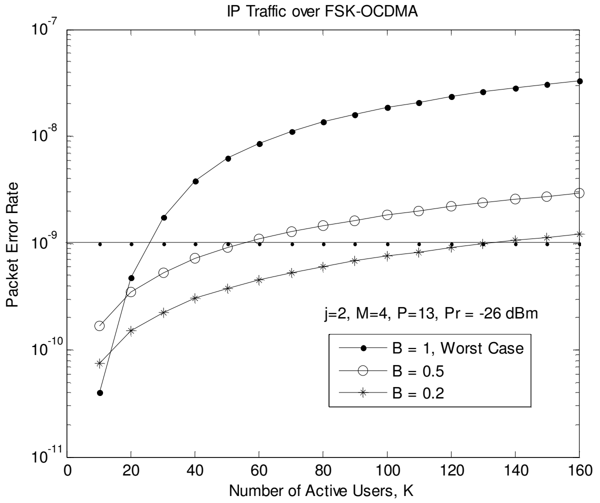

Fig. 4. PER of IP traffic over FSK-OCDMA network against number of active users, *K*

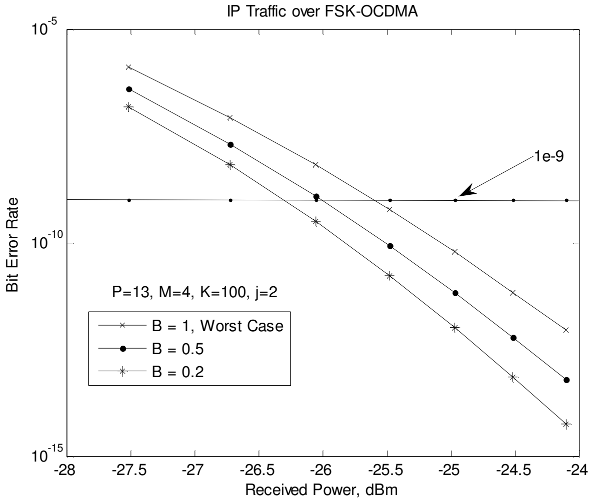

Fig. 5. BER of IP traffic over FSK-OCDMA network against received power, P_r

In Fig. 4 variations of PER against the number of active users for different channel utilizations is presented. The received power is still set to -26dBm. In this analysis, it is assumed that all IP traffic has a packet length of 1500 bytes (i.e. Ethernet local area network packet size). Therefore, the calculated PER is the estimation in the longest packet length condition. It is clearly shown that the performance of IP traffic becomes better with the reduction in the channel utilization. As observable from Fig. 4, while $B=1$, the busiest case, the PER degrades dramatically; although 25 users (15% of total users) are still accommodated with $BER = 10^{-9}$. When the probability that a user is active becomes relatively low, i.e. B=0.2 the network is able to hold $BER = 10^{-9}$ with serving 130 users. To compare again with the results in [16], the code-length here is shorter and the received power is smaller. This indicates the architecture's power efficiency and potentially higher throughput. To achieve a consistent overall network performance when each user in the network has a fixed average bit-rate, optimal channel utilization can be set for the network based on the network preferences and link budgets at the design stage. To support greater number of users, it is recommended to employ higher *P* and P_r values.

TABLE I
LINK PARAMETERS

Name	Symbol	Value
Optical Wavelength	λ_0	1553.5 nm
PD Quantum Efficiency	η	0.8
Linear Fiber-Loss Coefficient	α	0.2 dB/Km
Chip Duration	T_c	0.1ns
Fiber Length	L	10 Km
Packet Length	w	12000 bits

Fig. 5 presents the BER against the received power (P_r) for different channel utilizations. In this analysis 100 users (60% of total users) are assumed being involved in the transmission. As Fig. 5 noticeably shows, in order to mitigate the BER in busier cases higher power consumption can be a solution.

V. CONCLUSION

A novel IP traffic transmission architecture over the OCDMA local area network taking advantage of *M-ary* FSK has been proposed. It has been studied that reducing the channel utilization, increasing the repetition ratio and/or signal multiplicity can enhance the performance. The performance comparison with PPM revealed that this structure employing DPMPC is very power efficient and also can support greater number of active users. Furthermore, since each IP packet is buffered only twice at the edge of this network, similar to GMPLS, the buffer delay is significantly reduced compared with traditional routing schemes where IP packets are buffered at each hop. Also the optical encoder is adjusted for number of packets belonged to the same user instead of getting tuned for incoming IP packet individually. Accordingly, the architecture has a potential compatibility with IP/MPLS as well as burst switched networks. While the channel utilization as a parameter introduced in the analysis and architecture, this can be manipulated either dynamically or fixed for subscribers to have various services with different data-rates. This implies that the proposed scheme is able to support differentiated services (DiffServ) over OCDMA link.

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