Delay and Throughput Performance of Optical WCDMA Network with Code Sharing

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Abstract—**Wavelength, and code division multiple access (WCDMA) scheme employs both wavelength, and code concurrency. To increase the number of users supported by the network, code sharing is incorporated by using contention resolution protocols like ALOHA, and slotted ALOHA. Effect of code sharing on the network delay, and throughput performance has been analyzed.**

***Index Terms*—Code sharing, delay, throughput, WCDMA network.**

I. Introduction

All-optical networking concept promises an information transfer rate of terabits per seconds by requiring that no optoelectronic conversion occurs within the network, but only to its periphery. The most critical issue in the realization of such a network is how the resources will be shared among users, each requiring only a small portion of the total bandwidth. Multiple access schemes that are concurrent in nature, such as wavelength, time, and code division multiple access (WDMA, TDMA, and CDMA) are natural candidates for channel access in all-optical networks.

Networking issues such as multiple access mechanism, and access protocols must be guided by the capabilities of devices to implement them, and by the properties of optical channel. One such issue is the characteristics of tunable optical devices. The slow tuning speeds of optical devices impose important limitations on the feasibility of packet switching in a high speed all-optical network [1], [2]. This paper studies a multiple access scheme, called wavelength, and code division multiple access (WCDMA), that tries to reduce this effect.

The WCDMA is a hybrid of wavelength, and code division multiplexing. In this scheme, each wavelength is shared by a number of users through code multiplexing. This results in a smaller number of wavelengths in the network, and as a consequence reduces the effect of tuning delay on network performance. This scheme with code sharing by using contention resolution protocols like ALOHA, and slotted ALOHA leads to increase in the number of users supported by the network, but at the cost of degradation in network performance. Code sharing is also useful in optical CDMA context as it reduces the number of optical correlators at the receiver, hence the receiver complexity. Effect of code sharing on the network delay, and throughput performance is analyzed in this paper.

It is a well known fact that the network performance is significantly influenced by the access protocol with which the network users coordinate their transmission. In this paper, we have considered a simple, suboptimal access protocol that is based on circular search over the set of wavelengths [1].

II. Multiple Access Schemes

A. Wavelength Division Multiple Access

In WDMA, the optical bandwidth is divided into non-overlapping wavelength channels, and each channel is dedicated to a transmitter (or a receiver). When a user wants to communicate with another user, it informs the other party using an access protocol, and starts its transmission. The destination user tunes its receiver to the transmitter's channel, and starts its reception. This mode of WDMA requires fixed-tuned transmitters, and tunable receivers. A dual mode uses tunable transmitters, and fixed receivers. A tunable device has two important parameters: the tuning delay, and the tuning range. Optical filters e.g., tunable Fabry-Perot etalons have a tuning range as large as the fiber bandwidth, but also a large tuning delay typically in the range of 1 ms. On the other hand, lasers are faster in tuning, but they have a typical tuning range of about 5% of the fiber bandwidth. As optical filters are an integral part of all-optical network, tunability becomes a major issue on the efficiency of fast packet-switched optical WDMA networks.

B. Code Division Multiple Access

In CDMA, users are assigned distinct codes with appropriate orthogonality properties, and they use the entire frequency band at all times. Spreading of the information carrying the waveform over a broad frequency range provides immunity against a jammer with finite power, and robustness against frequency selective fading, and multipath interference. But optical CDMA suffers from significant multi-user interference as the intensity-based code words cannot be made completely orthogonal. In addition, the number of code words M in an optical orthogonal code, and consequently the number of supportable users is limited to [2-4]

$$M \le \frac{F-1}{W(W-1)} \quad (1)$$

where F is the number of chips per bit frame, and W the code weight. The value of F is dictated by how short a pulse the laser can generate, and by the bit rate. Decreasing the code

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weight W to increase M is not feasible as the error performance deteriorates with decreasing w. Thus, an optical CDMA (OCDMA) network has an inherent bottleneck in the number of users it can support.

C. Wavelength and Code Division Multiple Access

As mentioned earlier, WCDMA is a hybrid multiple access scheme that utilizes both wavelength, and code concurrency. In this scheme, the optical spectrum is divided into N/K channels where N is the number of users. Each frequency channel is shared by K transmitters via distinct code words. Due to the orthogonality provided by the wavelength division, same code word can be reused in different channels, thereby eliminating the user bottleneck of OCDMA. Further as the number of wavelength channels is reduced by a factor of K as compared to WDMA, the effect of slow tuning devices on network performance is less prominent.

D. WCDMA with Code Sharing

It is a modified form of hybrid WCDMA scheme. In this scheme, K transmitters in the above scheme are further grouped into K/m cells. All m users within a particular cell transmit their data using a common code in a contention mode of operation. Two users from different cells use different codes. Since all the users in a given cell use the same code to communicate with a particular receiver corresponding to that cell, intra-cell collisions occur. To resolve this issue of collisions within a cell, we use contention resolution protocols like ALOHA, and slotted ALOHA for m users within a cell.

The delay, and throughput performance of an optical network depends heavily on the multiple access protocol. A protocol specifies the mechanism with which network coordination is achieved in order to effectively share the network resources. Most access protocols for WDMA networks utilize control channels to coordinate the use of data channels. Control channels may be used on a contention-basis or they may be time-shared. In order to assess the performance of WCDMA with and without code sharing, a cyclic search access protocol is used.

III. CYCLIC SEARCH ACCESS PROTOCOL

We now describe a simple access protocol which uses a single time-shared control channel f_0, and M data channels f_1, . . . , f_M where $M = [N/K]$. The frequency channel f_j is used by K fixed-tuned transmitters T_k where $(j - 1)K + 1 < k < jK$. The control channel is shared by all N users, and therefore a time frame in the control channel is divided into N slots. In slot i, user i broadcasts the addresses of the users it wishes to communicate with as well as the status of its transmitter, and receiver. Transmitter (receiver) status indicates the receiver (transmitter) address the transmitter (receiver) is currently transmitting to (receiving from), if any. Each time slot is composed of three fields: N-bit backlog field **B,** $[\log_2 N]$-bit transmitter status field **T**, and another $[\log_2 N]$-bit receiver status field **R**. In time slot i, a packet backlog entry $B_j = 1$ indicates the existence of packets from transmitter T_i to receiver R_j. The transmitter status field **T** contains the address of the receiver that T_i is currently transmitting to. The receiver status field **R** is similarly structured. An ideal status is indicated by an illegal address sequence (e.g., all zero bits). The total control channel overhead is thus $N(N+2\log_2 N)$ bits per time frame. Each receiver cyclically scans the data channels searching for packets to receive. Upon tuning to f_k, a receiver R_j sequentially checks from the control channel whether a transmitter in f_k has packet for it, and whether that transmitter is available. If there is an available transmitter T_l in f_k, R_j indicates its readiness in the next control frame, and starts the reception phase. The service discipline is exhaustive i.e., a receiver leaves a transmitter only when there are no more packets for it at that transmitter. After completing its session with T_l, R_j checks the next transmitter T_{l+1} in the sequence. Once R_j has checked all K transmitters in f_k, and serviced all available ones in a single pass, it tunes to $f_{k \oplus 1}$ ($\oplus$ denotes modulo M addition) [1], [2], [4].

IV. PERFORMANCE OF WCDMA NETWORKS

In this section, analysis of network delay, and throughput has been carried out for both WCDMA, and WCDMA networks without and with code sharing. Subsequently, a comparative study of both the networks for different levels of code sharing is made.

A. Delay Analysis

(i) Without Code Sharing

The system is modeled as a collection of queues with multiple servers. In particular, each receiver is viewed as a server that cyclically attends the queues, and uses an exhaustive service discipline. Each transmitter consists of N queues, one per given destination. The queue Q_{ij} contains packet destined from transmitter T_i to receiver R_j. Thus a receiver can serve only one of the N queues at a transmitter. The arrival processes to the queues are assumed to be statistically independent Poisson processes, each with rate λ packets/s. The packet service times are presumed to be independent, and exponentially distributed with an expected value of b seconds. The buffers at the transmitter queues are assumed to be very large so that the buffer overflow events can be neglected. Finally, the tuning delay δ (in seconds) is defined as the time it takes a receiver to tune from one frequency channel to the next [1].

The queuing theoretic analysis of this network can be performed by viewing each receiver as a token in a logical token ring. In this model, there are N special tokens that are allowed to serve one particular queue out of N queues at a node (transmitter) on the ring. The nodes are grouped in groups of size K i.e., a group corresponds to one frequency channel. The "token travel time" from one group to another is δ (i.e., tuning time from one frequency channel to another). The system can be decomposed into N single-token logical rings with server vacations [1].

The average waiting time of a packet $E(W)$ normalized by the average packet duration in a WCDMA network is [1]

$$\frac{E(W)}{b} = \frac{\rho}{1-\rho} + \frac{N\bar{\delta}}{1-\rho}\left[\frac{1-N!\left(\rho/N\right)^N}{K(1-\rho)} - \frac{1}{2}\left(\frac{1}{K}+\frac{\rho}{N}\right)\right] \quad (2a)$$

where $\rho = N\lambda b < 1$ is the average load per receiver, and $\bar{\delta} = \delta/b$ the relative tuning delay. A closer inspection of the above delay expression shows that the waiting time experienced by a packet is composed of two distinct delay contributions. The first term is the irreducible M/M/1 delay which is due to the queuing of packets at the transmitters, while the second term is due to nonzero tuning delay.

For OCDMA network, the normalized average waiting time is given by

$$\frac{E(W)}{b} = \frac{\rho}{1-\rho} \tag{2b}$$

(ii) *With Code Sharing*

The delay introduced by code sharing using ALOHA protocol is given by [5]

$$D = T_d + \Delta\left(e^{2\rho^*} - 1\right) \tag{3}$$

Here T_d is the propagation delay, ρ^* (=$m\rho/N$) the load offered to the receiver due to m users which are sharing a common code, and Δ the time between the first, and second reception of a packet. In the following analysis, Δ is approximately taken equal to b. Further, in a high-speed optical network, T_d is considered to be negligibly small.

Due to symmetry, the receiver is equally likely to be at any optical channel frequency in the ring. Therefore, when a packet belonging to ith channel arrives, D_t delay occurs due to code sharing in accepting this packet, and it is given by

$$D_t = \frac{K}{N}\sum_{l=1}^{N/K} lD \tag{4a}$$

In the simplified form, it can be written as

$$D_t = \frac{1}{2}\left(\frac{N}{K}+1\right)D \tag{4b}$$

The average waiting time of a packet E(W) normalized by the average packet duration with code sharing under ALOHA scheme from (2a), (3), and (4b) will be,

$$\frac{E(W)}{b} = \frac{\rho}{1-\rho} + \frac{N\bar{\delta}}{1-\rho}\left[\frac{1-N!(\rho/N)^N}{K(1-\rho)} - \frac{1}{2}\left(\frac{1}{K}+\frac{\rho}{N}\right)\right] + \frac{1}{2}\left(\frac{N}{K}+1\right)\left[\exp\left(2\frac{m\rho}{N}\right)-1\right] \tag{5a}$$

and under slotted ALOHA, it is given by

$$\frac{E(W)}{b} = \frac{\rho}{1-\rho} + \frac{N\bar{\delta}}{1-\rho}\left[\frac{1-N!(\rho/N)^N}{K(1-\rho)} - \frac{1}{2}\left(\frac{1}{K}+\frac{\rho}{N}\right)\right] + \frac{1}{2}\left(\frac{N}{K}+1\right)\left[\exp\left(\frac{m\rho}{N}\right)-1\right] \tag{5b}$$

B. Network Throughput

To determine the network throughput, first we have to find out the blocking probability, P_b. It is the probability that a receiver does not find a transmitter of the ith packet available upon tuning to its channel frequency. Let p be the probability that receiver finds the transmitter of the ith packet available upon tuning to its channel i.e., $p = 1 - P_b$. Following [1], this probability is given by

$$p = \frac{1-\rho}{1-N!(\rho/N)^N} \tag{6}$$

Hence, P_b will be

$$P_b = 1 - \frac{1-\rho}{1-N!(\rho/N)^N} \tag{7}$$

The network throughput, β, can be calculated from Little's theorem

$$\beta = \frac{N\rho(1-P_b)}{E(W)} \text{ (packets received/s)} \tag{8}$$

Here $N\rho(1-P_b)$ is the effective total load in the network with N receivers, and ρ as defined earlier is the load per receiver [6]. Normalized delay, and throughput performance computed from (5), and (8) for ALOHA, and slotted ALOHA protocols for 64 users, 4 wavelength channels (implying K=16) are shown in Figs. 1, and 2, respectively for m=2, 4, and 8. In the same figures, results for no code sharing are also included for comparison purpose [4].

V. Conclusions

It is observed from the figures that optical WCDMA network delay, and throughput performance degrades with code sharing. With the increase in the code sharing, the degradation in the network performance, and the number of users supported by the network also increase. Therefore, a compromise has to be made between the two in deciding the level of code sharing. The degradation in delay and throughput performance with code sharing is more in case of ALOHA protocol than in slotted ALOHA protocol.

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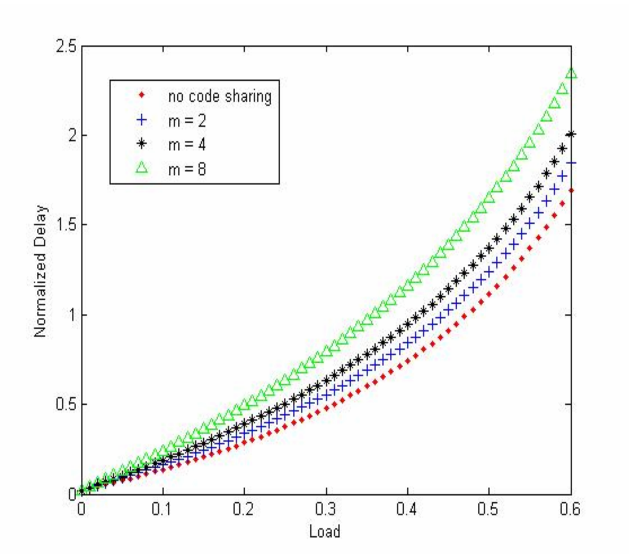
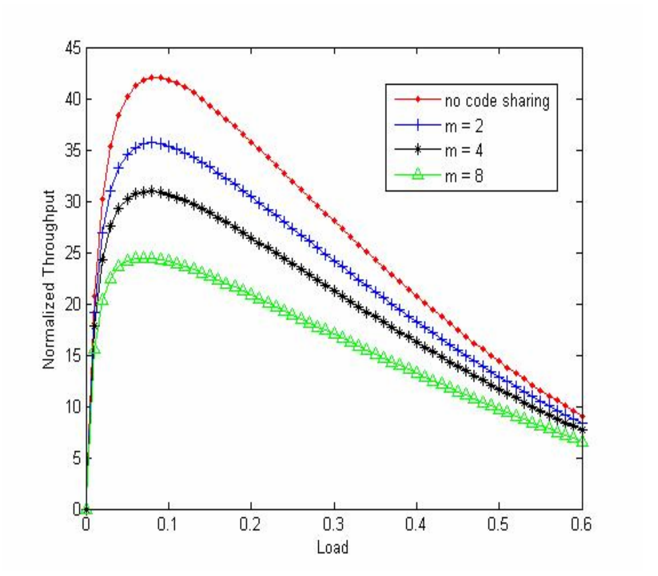
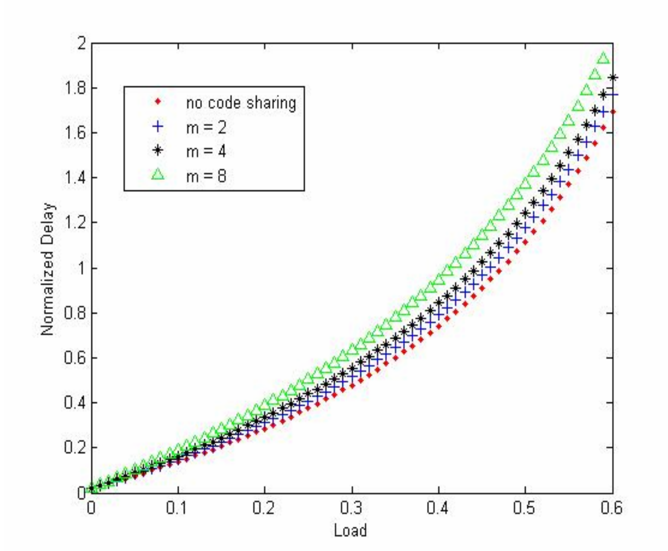


(a)

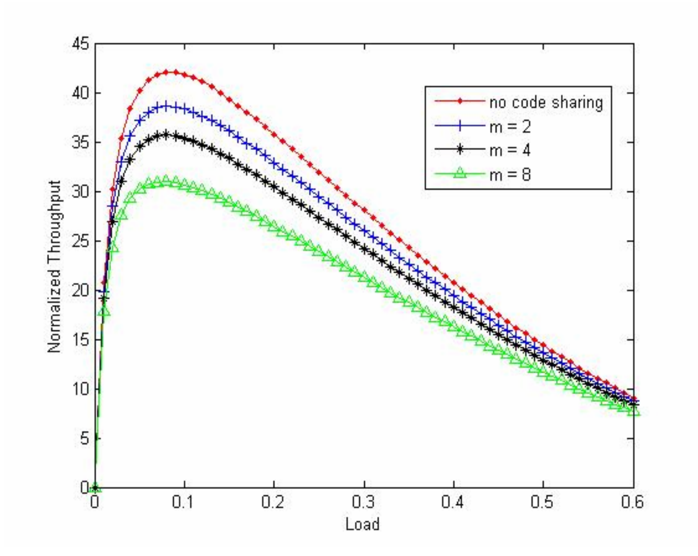


(b)

Fig. 1: WCDMA network normalized (a) delay, and (b) throughput performance with code sharing using ALOHA protocol for N = 64, K = 16, and $\bar{\delta}$ = 0.01.



(a)



(b)

Fig. 2: WCDMA network normalized (a) delay, and (b) throughput performance with code sharing using slotted ALOHA protocol for N = 64, K = 16, and $\bar{\delta}$ = 0.01.