On the Teletraffic Capacity of Optical CDMA

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***Abstract*— The capacity of an optical CDMA (OCDMA) network has traditionally been defined as the number of continuously transmitting circuits supported by the network. In this paper, we use teletraffic models to determine the teletraffic capacity of a circuit-switched OCDMA network where circuits carry bursty traffic. Our analysis is independent of the OCDMA implementation or spreading code. In conventional networks, e.g. a wavelength-routed-network (WRN), new circuits are blocked when all wavelengths are occupied. In OCDMA when the number of codewords exceeds number of network subscribers, new circuits need not be blocked. Instead, capacity is limited by multiple access interference: when the number of actively transmitting circuits becomes excessive, the BER of all circuits on the network degrades, causing an outage. We find that through statistical-multiplexing, the capacity of OCDMA exceeds that of a WRN except when circuit activity is very high while the constraints on outages are more stringent than those on blocking. In such cases, we show how OCDMA with call admission control can be used to match or exceed the capacity of a WRN. Overall, our analysis shows that OCDMA is well suited to applications when conventional blocking is undesirable, and/or circuits carry bursty traffic.**

***Index Terms*— Optical communication, Code division multiaccess, Queuing analysis.**

I. Introduction

In recent years there has been extensive research on the implementation of CDMA techniques in optical networks [1]. In optical CDMA (OCDMA), communication channels are created by allocating a unique codeword to each user that spreads each user's signal in time, wavelength, phase, etc., so that multiple users can occupy the entire optical bandwidth simultaneously. Much of the work on OCDMA has been motivated by a desire to achieve the unique system-level advantages of CDMA in the optical domain. However, while OCDMA has the key advantage of being able to support multiple *intermittently* transmitting users broadcasting on different channels (*i.e.* different codewords), the capacity of an OCDMA network has traditionally been defined as the number of *continuously* transmitting users supported by the network. In this paper, we study a network with stochastic utilization in order to determine the teletraffic capacity of OCDMA and to understand the statistical multiplexing properties of an OCDMA network.

In traditional multiple access schemes, where multiple users communicate over a shared media by broadcasting on different communication channels, new users to the media are *blocked* when all available channels are occupied. For example, in a wavelength routed network (WRN), each user is assigned to a unique wavelength channel as long as there are wavelengths available, after which new users are blocked until a wavelength becomes free. In contrast with traditional schemes, a key advantage of CDMA is that blocking need not occur, since there is no hard limit on the number of communication channels (*i.e.* codewords) that are available when spreading codes with high cardinality are used.[1] Instead, the number of users that can be accommodated by the network is limited by multiple access interference (MAI); the MAI increases as more users access the media, causing a graceful degradation in the bit error rate (BER) performance of users on the system. We say that an *outage* occurs when interference causes the average performance of *all* users on the media to degrade beyond a particular maximum BER threshold. Therefore, the *outage probability* is the measure of the service availability of a CDMA system. As such, the number of users a CDMA system can accommodate can be determined by the performance (*i.e.* BER) and service availability (*i.e.* outage probability) thresholds set by network operators, rather than by the number of available channels as in traditional multiple access schemes. Additionally, a CDMA system can be used efficiently by a large number of intermittently transmitting users, since performance is limited only by the number of users simultaneously transmitting (and therefore creating interference) at a particular instant. Thus, CDMA has the advantage of achieving *statistical-multiplexing* directly at the physical level of the network. This statistical multiplexing property can be exploited to increase capacity.

In this paper we use teletraffic models, inspired by the work on wireless cellular CDMA systems in [2]–[4][2] to provide an analytic framework for determining the *teletraffic capacity* of a circuit-switched OCDMA network. We define the teletraffic capacity as the average number of circuits that can be accommodated by the network for a particular maximum outage and/or blocking probability. We show how OCDMA increases the teletraffic capacity of the network, particularly in applications when conventional blocking is undesirable, and/or when the network supports intermittently transmitting users. Our analysis is independent of the spreading code used by the OCDMA network.

We begin by clarifying our use of the term capacity. From the information-theoretic perspective, the *channel capacity* is the maximum possible bit rate for error-free transmission achievable by a system in the presence of noise. The channel capacity of an OCDMA system is analyzed in [5]. In the experimental community, capacity describes the number

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[1] That is, when there are fewer subscribers than available codewords.

[2] Our analysis differs from [2]–[4] in that we model an optical system with no stochastic fading, multipath, or other-cell-interference, and we assume a fixed number of subscribers instead of Poisson arrivals of circuit requests.

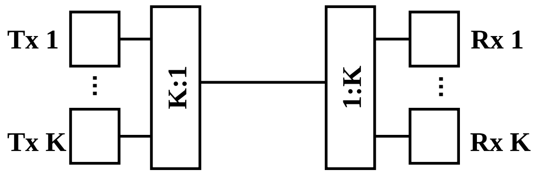


Fig. 1. Broadcast-and-select network with K subscribers. Signals from K transmitters, each tuned to an available channel, are passively combined by a $K : 1$ coupler and sent via a single fiber to a $1 : K$ coupler that splits the combined signal between K receivers, each tuned to a particular channel.

of *simultaneously transmitting* users that may be supported by a system with particular data rates, receive powers and maximum allowable bit error rates (BER) [6]. However, in practical circuit-switched networks, we need not assume that all users are constantly transmitting data. Instead, traffic is stochastic; at a given instant some subscribers may not have a circuit connected to the network. Moreover, each connected circuit may only be *active*, or carrying data, intermittently. Thus, to take into account the stochastic nature of traffic, we evaluate the teletraffic capacity, or the average number of circuits that can be carried by a network designed to operate with a particular performance quality (maximum allowable BER), service availability (maximum outage probability), and maximum blocking probability. Because of the stochastic nature of circuit-switched networks, the teletraffic capacity can greatly exceed the network capacity quoted by the experimental community.

We compare the teletraffic capacity of a circuit-switched wavelength-routed network (WRN) with traditional blocking characteristics (*i.e.* new users are blocked when all available wavelengths are in use) to that of a circuit-switched, interference-limited, OCDMA network. We model the simple fiber-optic broadcast-and-select networks with K subscribers shown in Fig. 1; that is, K transmitters that create a circuit connection to the network by tuning to an available channel (WRN wavelength or OCDMA codeword), are passively coupled via a single optical fiber to K receivers that selectively listen to a particular channel (via wavelength filtering or code correlation). These networks are representative of broadcast-and-select local area networks (LANs), or $K \times K$ optical switch fabrics that can be used inside an Internet router or as an optical interconnect, or half-duplex passive optical networks (PONs) where a root node with a number of parallel transceivers is connected to K subscribers via a passive optical coupler. In fact, our analysis applies to any broadcast-and-select network with tunable transmitters, tunable receivers or both, where K users operate in half-duplex mode or $K/2$ users operate in full-duplex mode while coupled to a single fiber. Furthermore, these networks form the building blocks for more complex multi-hop networks, where hops are interconnected via optical fibers carrying broadcast-and-select traffic.

We begin our analysis by modelling a circuit-switched OCDMA network without blocking. We assume that all new circuit requests are carried by the network, and determine the maximum load that can be carried by the network while satisfying the performance quality (maximum allowable BER) and service availability (maximum outage probability) constraints. We compare the capacity of OCDMA to that of a WRN. We then determine the capacity of an OCDMA network that uses call admission control (CAC). With call admission control, the network blocks some new circuit requests in order to reduce the occurrence of outages. We analyze two protocols, a *complete sharing* CAC protocol, that uses a centralized controller to grant circuit requests based on the number of established circuits on the network, and a *check-interference-upon-call-arrival (CIUCA)* CAC protocol, that uses a controller to grant circuit requests based on observed interference power levels. Finally, we discuss situations in which OCDMA (with and without CAC) can be used to increase network capacity beyond that obtained with a traditional blocking system such as a WRN.

II. OCDMA and WRN Teletraffic Models

We state our modelling assumptions here and refer the reader to the appendix for a glossary of symbols. We model WRN and OCDMA broadcast-and-select networks with exactly K subscribers that connect to the network on a circuit-by-circuit basis. We assume that the datastream transmitted on each circuit is bursty, so that on average each circuit will carry data with probability p, and carry no data with probability $1 - p$. For traditional voice traffic, [7] showed empirically that $p \simeq 40\%$. For data traffic, circuit activity p is highly dependant the application generating the traffic, but data traffic typically has lower circuit activity than voice traffic [8]. (See Section III-D for more on circuit activity.)

The number of circuits established on the network at time t is a random variable $N(t)$. The holding time of each circuit (from circuit connection to disconnection) may be modelled as a random variable with an *arbitrary* distribution but finite mean $\frac{1}{\mu}$ [hours]. We assume that each of the K subscribers will generate a new circuit request T [hours] after his or her current circuit connection is released from the network. We further assume that T is a random variable with *arbitrary* distribution but with a finite mean $\frac{1}{\nu}$ [hours]. We define $r = \frac{\nu}{\mu}$ as the *offered circuit load per free subscriber* [9], [10]. Offered load may be interpreted as a normalized circuit request arrival rate, or the average number of new circuit requests arriving during the average circuit holding period from a subscriber without a connection to the network. The aggregate offered circuit load [10] is the average number of circuits that would be carried by the system if no calls were rejected due to lack of channels (*i.e.* if the number of channels was infinite).[3] For our models, the aggregate offered circuit load is $a = K\frac{r}{r+1}$.

A. Wavelength Routed Network (WRN) model

We consider a WRN with K subscribers where each subscriber can transmit on any of the Γ available wavelengths. We want to compare the teletraffic capacities of WRN and

[3]Some sources [9] define aggregate offered load as $a = E[(K - N)r]$ (the aggregate offered load from the $K - N$ subscribers that do not already have circuits connected to the network) so that a is dependant on loss model parameters. We do not use this definition because it complicates comparisons across systems with different distributions for N.

OCDMA directly at the physical layer (without multiplexing at higher layers), so we assume that each wavelength on the WRN can carry at most one circuit. Circuits are established as long as there are wavelengths available, after which all incoming new circuit requests are blocked and cleared from the network.

We model the WRN (with circuit inter-arrival and holding times distributions as above) using the generalized Engset loss model, denoted $G(K)/G/\Gamma(0)$ in [9], (or $G/G/\Gamma/\Gamma/K$), where the K sources represent subscribers, and the Γ servers represent wavelength channels. Assuming that the number of circuits established on the network $N(t)$ is a stationary random process over some interval, we can write it as a random variable N. It is shown in [9] (or [11] Thrm 6.1) that N has truncated binomial distribution

$$P[N=n] = \frac{\binom{K}{n} r^n}{\sum_{i=0}^{\Gamma} \binom{K}{i} r^i}$$

for $0 \leq N \leq \Gamma$. The probability that an incoming circuit request will be blocked, or the *call congestion*,[4] is given by Engset's loss formula (see [11] Eqn 6.13) as

$$P_{block} = \frac{\binom{K-1}{\Gamma} r^{\Gamma}}{\sum_{i=0}^{\Gamma} \binom{K-1}{i} r^i} \tag{1}$$

Over an interval where $N(t)$ is stationary, the *aggregate carried circuit load*, or the average number of circuits carried by the network [9], [10], is

$$a_c = E[N] = Kr \frac{\sum_{n=0}^{\Gamma-1} \binom{K-1}{n} r^n}{\sum_{i=0}^{\Gamma} \binom{K}{i} r^i} \tag{2}$$

where $E[\cdot]$ denotes expectation. We define the teletraffic capacity of the WRN by the maximum value of a_c such that the blocking probability does not exceed a *blocking constraint* $P_{block}^{\max}$ defined by network operators (*i.e.* $P_{block} < P_{block}^{\max}$).

B. Optical CDMA (OCDMA) model

We consider an OCDMA network where performance is limited by multiple access interference (MAI) rather than by noise, and bit errors occur when a signal becomes buried in MAI such that it cannot be de-spread and recovered correctly. We further assume that the network is power-controlled so that all circuits arrive at the receiver with equal power, and therefore all circuits create an equal amount of interference. We say that an *outage* occurs when the performance (BER) of the circuits on the network degrades beyond a maximum BER threshold. Since bit errors are caused by MAI, the BER is a function of the number of *simultaneously transmitting* circuits. As such, we need to determine the *outage threshold* Γ, or the maximum number of circuits that may be simultaneously active on the network for a given BER threshold, by analyzing the characteristics of the OCDMA spreading code. For a complete discussion of how to determine Γ for a particular spreading code and BER threshold we refer the reader to e.g. [1], [12]–[20]. (Note that in the works cited here, Γ, the number of simultaneous users accommodated by the system, is sometimes refereed to as the capacity of the system.) However, we state here that in general, longer codewords with more wavelengths, timeslots, etc. and lower correlation between different codewords will yield higher values of Γ. Since one factor (among many) that limits codeword length is the system's data rate per user, it follows that Γ is also limited also by the system's data rate per user. As an example, we reproduce in Fig. 2 a plot of the BER vs the number of simultaneously active circuits from our recent incoherent asynchronous OCDMA testbed [21]. From Fig. 2, we see that when the maximum BER threshold is 10^{-9}, it follows that $\Gamma \approx 50$ (for a 1.5 ps sampling window. See [21].)

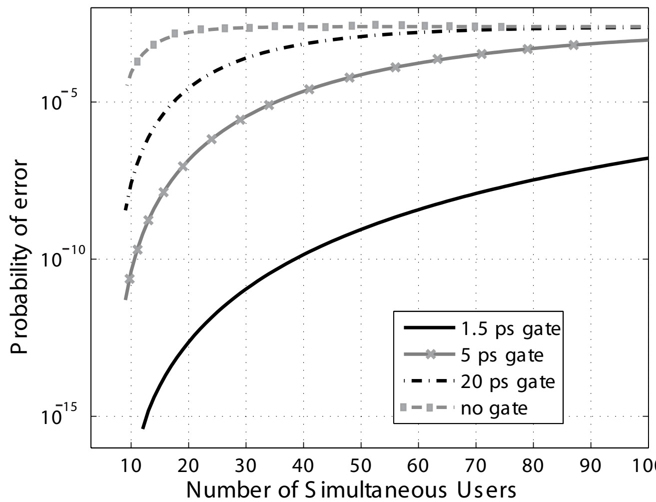


Fig. 2. Reproduction of Fig. 6 in [21] that can be used to find Γ for [21]'s system. Probability of error versus number of simultaneously active circuits, for an 8-wavelength, 23-timeslot incoherent asynchronous OCDMA network using optical time gating with various optical sampling windows.

We assume here that the cardinality of the OCDMA spreading code is greater than the number of subscribers, so that any time one of the K subscribers attempts to establish a circuit there will always be a codeword available. Therefore, when call admission control is not used, traditional blocking does not occur. However, when $M(t)$, the number of *simultaneously active* circuits on the network at time t, exceeds the outage threshold Γ, we say that an outage occurs with probability

$$P_{outage} = P[M > \Gamma] \tag{3}$$

where we assume that $M(t)$ and $N(t)$ are a stationary processes over some time interval, so that we can drop the time index and rewrite them as a random variables N and M. Note that (3) implies that OCDMA provides statistical multiplexing of bursty datastreams directly at the physical layer, because the outage probability depends on M (the number of simultaneously active circuits that create interference), rather than N (the number of connected circuits) and $M \leq N$.

Because we assume an OCDMA spreading code of high cardinality, we can model this system (with circuit inter-arrival and holding times distributions as above) as a finite-

[4]In this paper, we take the blocking probability as a measure of the user-perceived quality of service. As such, we model blocking from the point of view of an new circuit request (*i.e.* call congestion, P[A new circuit request arrives when $N = \Gamma$]), rather than from the point of view of the network operator (*i.e.* time congestion, $P[N = \Gamma]$).

K source, infinite server queue, denoted by $G(K)/G/\infty$ in [9] (or $G/G/\infty/\infty/K$), where the K sources represent subscribers and the infinite servers represent codeword channels. Then the number of connected circuits, N, is a binomial random variable with probability distribution $P[N = n] = \binom{K}{n} r^n (1+r)^{-K}$ for $0 \leq N \leq K$ (see [9] or [11] Eqn 6.3) where r is the offered circuit load per free subscriber. Because of the bursty nature of the data on each circuit, the number of circuits simultaneously carrying data, M, has probability distribution

$$P[M = m] = \sum_{n=m}^{K} \binom{n}{m} p^m (1-p)^{n-m} \cdot P[N = n] \quad (4)$$
$$= \binom{K}{m} \alpha^m (1+\alpha)^{-K}$$

where $\alpha = pr/(1 + (1-p)r)$. The outage probability is now

$$P_{outage} = P[M > \Gamma] = \sum_{m=\Gamma+1}^{K} \binom{K}{m} \alpha^m (1+\alpha)^{-K} \quad (5)$$

The aggregate carried circuit load[5] is $a_c = E[N] = K\frac{r}{r+1}$. We define the teletraffic capacity of the OCDMA network by the maximum value of a_c such that the outage probability does not exceed an *outage constraint* $P_{outage}^{\max}$ defined by the network operators (*i.e.* $P_{outage} < P_{outage}^{\max}$). Note that for an OCDMA network without call admission control, $P_{block} = 0$.

C. Comparison of WRN and OCDMA

In Figs. 3-4 we compare the teletraffic capacity of an OCDMA network with K subscribers and outage threshold Γ (the maximum number of circuits that may be simultaneously active for a given maximum BER threshold), to a WRN with K subscribers and Γ wavelengths ($\Gamma \leq K$), for various values of circuit activity p.[6] We assume that both systems carry circuits that operate at the same bit rate, so that the capacity of the two systems may be compared by determining the average number of circuits that can accommodated by the network while satisfying the appropriate outage or blocking constraints. This is a valid assumption since OCDMA networks are typically designed so that the data rate of each OCDMA channel is comparable to the data rate of a single wavelength channel in a WRN. As an example, consider [21] our recent wavelength-hopping time-spreading OCDMA testbed that uses an 8-wavelength, 23-timeslot spreading code. The system is designed so that each OCDMA channel operates at a data rate of 5 Gb/s, which means the the *chip-rate* for each user is 23 chips/bit * 5 Gb/s = 115 Gchip/s. Note that the chip-rate for each OCDMA channel is much *higher* than that of a typical WRN channel, while the bit-rate of an OCDMA channel is comparable to a WRN with channel bit-rates of 5 Gb/s. This is because for both OCDMA and WRN systems, pulses are typically generated at the channel bit rate using some form of electronic modulation. However, in OCDMA, these pulses are optically manipulated to generate codewords with chip-rates much higher than the channel bit-rates. (See [1] for more details.) For example in [21], optical pulses generated at a rate of 5 Gb/s are then placed in one of 23 possible timeslots using fiber optic delay lines. Furthermore, Fig. 2 indicates that for [21] system has $\Gamma \approx 50$ for a maximum BER threshold of 10^{-9}. Therefore, [21]'s OCDMA system may be compared to a WRN using $\Gamma \approx 50$ wavelengths where each wavelength channel operates at a bit rate of 5 Gb/s.

Recall that the blocking probability of the WRN depends only on the number of *connected* circuits N, since we model a system that does not support grooming of multiple bursty circuits onto a single wavelength. Therefore, the teletraffic capacity of the WRN (the maximum value of $a_c = E[N]$ such that $P_{block} < P_{block}^{\max}$) is independent of p. However, the outage probability of the OCDMA network depends on the number of *active* circuits M, and is therefore a function of circuit activity p. As such, the teletraffic capacity of an OCDMA network (the maximum value of $a_c = E[N]$ such that $P_{outage} < P_{outage}^{\max}$) is strongly dependant on p.

The statistical-multiplexing property of OCDMA is evident from Figs. 3-4. Because the OCDMA network is interference-limited, when transmission is very bursty ($p \to 0$) the total interference on the network decreases, causing the outage probability to decrease, and the teletraffic capacity to increase. We can confirm this by approximating (1) and (5) for small r by $P_{outage} \approx \binom{K}{\Gamma+1}(pr)^{\Gamma+1}$ and $P_{block} \approx \binom{K-1}{\Gamma} r^{\Gamma}$. Therefore, if p is small then $P_{outage} < P_{block}$ and the teletraffic capacity of OCDMA exceeds that of the WRN. However, when transmissions are less bursty ($p \to 1$) the outage probability of OCDMA is comparable to the blocking probability of the WRN.

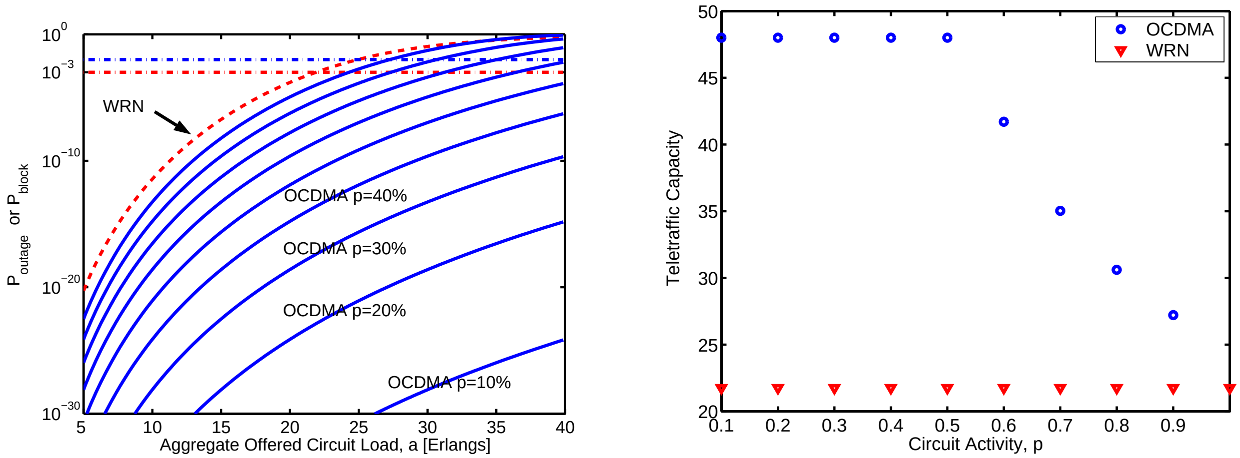
To compare the teletraffic capacity of the two systems, we first discuss the nature of the outage and blocking constraints, $P_{outage}^{\max}$ and $P_{block}^{\max}$. If it is more important to accommodate new circuits on the network than it is to ensure the quality of service of existing circuits (so that $P_{outage}^{\max} > P_{block}^{\max}$), then the teletraffic capacity of OCDMA is higher than that of the WRN, as in Fig. 3. However, if it is more important for the network preserve the quality of service of existing circuits before it grants new circuit requests (so that $P_{outage}^{\max} < P_{block}^{\max}$), then when the circuit activity is very high ($p \to 1$), the WRN can have higher teletraffic capacity than the OCDMA network. However, even in a situation when $P_{outage}^{\max} < P_{block}^{\max}$, the teletraffic capacity of OCDMA is often higher than that of the WRN when circuit activity is low ($p \to 0$), especially if Γ is not much smaller than the number of subscribers K, as in Fig. 4.

III. Call Admission Control for OCDMA

With call admission control (CAC), the network blocks some new circuit requests in order to reduce interference on the network so that the outage probability decreases. However, this improvement in service availability comes at the cost of a non-zero blocking probability.

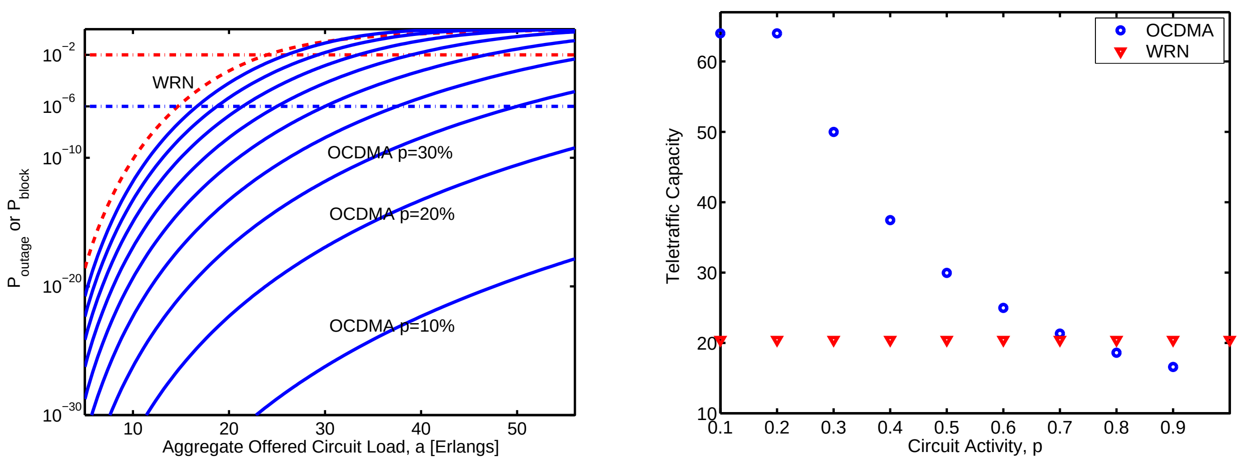
[5] There is no blocking so carried load a_c is equal to offered load a.

[6] We could have compared OCDMA to WRN on basis of the number of wavelengths occupied by each system. However, for OCDMA the relationship between outage threshold Γ and the number of wavelengths used in the system is dependant on the spreading code. Since our analysis here is independent of the OCDMA code, we have chosen to compare systems on the basis of the number of simultaneously active channels that each can support.



(a) (b)

Fig. 3. $K = 48$ subscribers and $\Gamma = 32$. The operating constraints are $P_{outage}^{\max} = 10^{-2}$ and $P_{block}^{\max} = 10^{-3}$. (a) P_{outage} versus a, aggregate offered circuit load for OCDMA with circuit activity ranging from $p = 10\%$ to $p = 90\%$. P_{block} versus a for WRN. (b) Teletraffic capacity versus circuit activity p.



(a) (b)

Fig. 4. $K = 64$ subscribers and $\Gamma = 32$. The operating constraints are $P_{outage}^{\max} = 10^{-6}$ and $P_{block}^{\max} = 10^{-2}$. (a) P_{outage} versus a, aggregate offered circuit load for OCDMA with circuit activity ranging from $p = 10\%$ to $p = 90\%$. P_{block} versus a for WRN. (b) Teletraffic capacity versus circuit activity p.

We begin our analysis of call admission control by supposing that the OCDMA network should be operated with perfect service availability, so that outages *never* occur. Thus, to ensure that $P_{outage} = 0$ for any load, it follows that no more than $N = \Gamma$ circuits can ever be connected to the network. To do this, the network requires a centralized CAC controller that records N, the number of connected circuits on the network, and blocks arriving requests when $N = \Gamma$. In this case, the OCDMA network becomes a traditional blocking network with capacity equivalent to that of a WRN with Γ wavelengths. However, this scheme can severely limit the teletraffic capacity of network, since it eliminates the capacity gained through statistical multiplexing. The capacity of the network can greatly increase if outages are allowed to occur with some small probability. Therefore, the problem of designing a call admission controller reduces to finding the optimal algorithm for blocking new circuit requests such that operating constraints on outage and blocking, $P_{outage}^{\max}$ and $P_{block}^{\max}$, are met while maximizing the teletraffic capacity.

We have analyzed two simple CAC protocols: The *complete sharing (CS)* CAC protocol uses a centralized controller that records the number of connected circuits on the network N, and blocks arriving requests when $N = B$. The *check-interference-upon-call-arrival (CIUCA)* CAC protocol uses a controller that learns the number of active circuits M by sensing power levels, and blocks requests when $M \geq B$. We begin by defining the design goals for these CAC protocols. We then develop teletraffic models for each protocol, and finally compare our protocols using these models.

A. CAC Design Goals

The design goal for a CAC controller is to find an algorithm for blocking new circuit requests that maximizes the teletraffic capacity, *i.e.* to maximize aggregate carried circuit load a_c

while satisfying the following two operating constraints:

1) *Outage Constraint:* Ensure that outages occur with probability $P_{outage} < P_{outage}^{\max}$.
2) *Blocking Constraint:* Ensure that new circuit requests are blocked with probability $P_{block} < P_{block}^{\max}$.

We can achieve our design goal for the CS and CIUCA protocols by finding the optimal blocking threshold B^* such that aggregate carried load a_c is maximized for a network with a known number of subscribers K, outage threshold Γ, circuit activity p, and constraints $P_{outage}^{\max}$ and $P_{block}^{\max}$. We do this using a simple exhaustive search of complexity $\mathcal{O}(K)$:

1) Check if CAC is required. If $P_{outage} < P_{outage}^{\max}$ in (5) for all r, then the outage constraint is satisfied with *any* load for an OCDMA network without CAC, so CAC is not required. Otherwise, CAC is required, set $B = 1$, and continue to step 2.
2) For an OCDMA network using CAC with blocking threshold B, compute the maximum offered load per free subscriber $r_B^{\max}$ that satisfies the outage and blocking probability constraints. Since aggregated carried circuit load $a_c = E[N]$ is an increasing function of r (for fixed B and K) use $r_B^{\max}$ to compute the maximum a_c for this value of B.
3) Increment B by 1 and repeat step 2 as long as $B \leq K$.
4) Choose the B that achieves the largest maximum value of a_c. This is the optimal blocking threshold B^*.

B. Complete Sharing (CS) CAC model

In the complete sharing call admission control (CS CAC) model, new circuit requests are granted until the number of circuits established on the network reaches the blocking threshold B. In other words, new circuit requests are blocked when $N = B$, and as before, outages occur when $M > \Gamma$. Using the assumptions in Section II, we model the network with the $G(K)/G/B(0)$ generalized Engset loss model (where the K sources represent subscribers, and the B servers represent the OCDMA circuits that the CAC controller allows to connect to the network). Thus the blocking probability due to the CS CAC controller is given by Engset's loss formula as

$$P_{block} = \frac{\binom{K-1}{B} r^B}{\sum_{i=0}^{B} \binom{K-1}{i} r^i} \tag{6}$$

To determine the outage probability $P_{outage} = P[M > \Gamma]$, we first find the distribution of the number of active circuits, M for $0 \leq M \leq B$ from

$$\begin{aligned} P[M = m] &= \sum_{n=m}^{B} P[M = m|N = n] \cdot P[N = n] \qquad (7) \\ &= \sum_{n=m}^{B} \binom{n}{m} p^m (1-p)^{n-m} \frac{\binom{K}{n} r^n}{\sum_{j=0}^{B} \binom{K}{j} r^j} \end{aligned}$$

so that the outage probability is

$$P_{outage} = \frac{\sum_{m=\Gamma+1}^{B} \sum_{n=m}^{B} \binom{n}{m}\binom{K}{n} (pr)^m ((1-p)r)^{n-m}}{\sum_{j=0}^{B} \binom{K}{j} r^j} \tag{8}$$

Note how outages become more probable and blocking becomes less probable as the blocking threshold B increases. The aggregate carried circuit load is given by

$$a_c = E[N] = Kr \frac{\sum_{n=0}^{B-1} \binom{K-1}{n} r^n}{\sum_{i=0}^{B} \binom{K}{i} r^i} \tag{9}$$

To operate the network without outages ($P_{outage} = 0$), we set the blocking threshold $B \leq \Gamma$ so that the CS CAC protocol reduces the OCDMA network to a traditional blocking system such as a WRN. Furthermore, when $B = K$ no new circuit requests are blocked, and this scheme operates like an OCDMA network without CAC.

C. Check Interference on Call Arrival (CIUCA) CAC model

In the check-interference-upon-call-arrival (CIUCA) protocol, the CAC controller learns the number of active circuits M by sensing power levels, and blocks new circuit requests when $M \geq B$. As always, outages occur when $M > \Gamma$. With this protocol, the probability that a new circuit request is granted depends both on the number of circuits already connected, N, and the circuit activity p. We define a state-dependant blocking probability $1 - \beta_n$ from

$$\begin{aligned} \beta_n &= P[M < B | N = n] \\ &= \begin{cases} 1 & 0 \leq n < B \\ \sum_{m=0}^{B-1} \binom{n}{m} p^m (1-p)^{n-m} & B \leq n \leq K \end{cases} \end{aligned} \tag{10}$$

To develop a teletraffic model for this protocol we start by strengthening two of the assumptions we made in Section II. Instead of assuming that the holding time of each circuit is an arbitrary random variable, we now model circuit holding time as an *exponential* random variable with mean $\frac{1}{\mu}$. We also assume that the time between subsequent circuit requests, T, is an *exponential* random variable with mean $\frac{1}{\nu}$. These assumptions allow us to model the evolution of the number of circuits connected to network $N(t)$ as a Markovian birth-death process [22]. Our model has state-dependant birth rates $\lambda(n)$ and death rates $\mu(n)$ when $N(t) = n$ as follows:

$$\begin{aligned} \lambda(n) &= (K-n)\nu \cdot \beta_n && 0 \leq n \leq K \\ \mu(n) &= n\mu && 1 \leq n \leq K \end{aligned}$$

If assume that $N(t)$ is stationary over some time interval (writing it as N) we can determine the state probabilities $P[N = n]$ from the well-known balance equation [22] $\lambda(n-1)P[N = n-1] = \mu(n)P[N = n]$ as

$$P[N = n] = \frac{\binom{K}{n} r^n \prod_{j=0}^{n-1} \beta_j}{\sum_{i=0}^{K} \binom{K}{i} r^i \prod_{j=0}^{i-1} \beta_j} \tag{11}$$

where $r = \frac{\nu}{\mu}$ is the offered circuit load per free subscriber. It turns out that (11) is valid even when inter-arrival times and circuit holding times are *arbitrarily* distributed [23], [24]. The blocking probability is $P_{block} = P[\text{A new circuit request arrives when } M \geq B]$. To determine P_{block} we begin by using (10)-(11) to find

$$P[M \geq B] = \sum_{n=0}^{K} P[M \geq B | N = n] P[N = n]$$
$$= 1 - \frac{\sum_{n=0}^{K} \binom{K}{n} r^n \prod_{j=0}^{n} \beta_j}{\sum_{i=0}^{K} \binom{K}{i} r^i \prod_{j=0}^{i-1} \beta_j}$$

so that the blocking probability can be obtained using the arrival theorem [9]

$$P_{block} = 1 - \frac{\sum_{n=0}^{K-1} \binom{K-1}{n} r^n \prod_{j=0}^{n} \beta_j}{\sum_{i=0}^{K-1} \binom{K-1}{i} r^i \prod_{j=0}^{i-1} \beta_j} \quad (12)$$

As usual, we find the distribution of the number of active transmissions M using (4) and (11). The outage probability is then $P_{outage} = P[M > \Gamma] =$

$$\frac{\sum_{m=\Gamma+1}^{K} \binom{K}{m} (pr)^m \sum_{\ell=0}^{K-m} \binom{K-m}{\ell} ((1-p)r)^\ell \prod_{j=0}^{\ell+m-1} \beta_j}{\sum_{i=0}^{K} \binom{K}{i} r^i \prod_{j=0}^{i-1} \beta_j} \quad (13)$$

Note that when blocking threshold B increases, the β_n increase as well, so that outages become more probable and blocking less probable. Finally, we find the carried load as

$$a_c = E[N] = Kr \frac{\sum_{n=0}^{K-1} \binom{K-1}{n} r^n \prod_{j=0}^{n} \beta_j}{\sum_{i=0}^{K} \binom{K}{i} r^i \prod_{j=0}^{i-1} \beta_j} \quad (14)$$

When the blocking threshold $B = K$, this scheme reduces to an OCDMA network without CAC, with $P_{block} = 0$ and $\beta_n = 1$ for $n \leq K$. However, it is impossible to completely prevent outages ($P_{outage} = 0$ for all r) with this protocol. Because requests are blocked on the basis of interference levels, it is impossible to ensure that the number of *connected* circuits N does not exceed Γ. In other words, with the CIUCA protocol there is a non-zero probability β_N that for any blocking threshold B a new circuit request will be granted when $N > \Gamma$ and therefore possibly cause an outage.

D. Comparison of CAC Protocols

The purpose of CAC in an optical CDMA network is different from that of the CAC deployed in wireless cellular CDMA systems (e.g. [4], [25]). In a cellular system, the number of potential subscribers is infinite, so that number of circuits requests carried by the network can be infinite as well. Therefore, new circuit requests should be blocked to ensure that the network meets the outage probability constraints with optimal capacity. However, since a fiber optic network typically has finite number of subscribers K, the maximum carried circuit load $a_c = E[N]$ is also finite and limited to K. Therefore, CAC is not required for an OCDMA network where the outage probability is strictly less than $P_{outage}^{\max}$ for all loads, (e.g. the systems in Fig. 3 with circuit activity $p \leq 50\%$).

If the OCDMA network should be operated with perfect service availability, so that outages *never* occur ($P_{outage}^{\max} = 0$), CS CAC with $B^* = \Gamma$ should be used to ensure that number of connected circuits on the network never exceeds $N = \Gamma$. In this case, the OCDMA network becomes a traditional blocking network with capacity equivalent to that of a WRN with Γ

TABLE I

TELETRAFFIC CAPACITIES FOR OCDMA AND WRN FOR DIFFERENT BLOCKING AND OUTAGE CONSTRAINTS WHEN $K = 64, \Gamma = 32, p = 0.65$.

$P_{outage}^{\max}$	$P_{block}^{\max}$	OCDMA	CS-CAC	CIUCA-CAC	WRN
10^{-2}	10^{-6}	36.3	36.3	36.3	14.7
10^{-2}	10^{-5}	36.3	36.3	36.3	16.2
10^{-2}	10^{-4}	36.3	36.3	36.3	17.9
10^{-2}	10^{-3}	36.3	36.3	36.3	20.4
10^{-2}	10^{-2}	35.9	36.3	36.2	23.6
10^{-3}	10^{-2}	31.5	32.7	32.3	23.6
10^{-4}	10^{-2}	28.2	29.7	29.3	23.6
10^{-5}	10^{-2}	25.4	27.6	26.9	23.6
10^{-6}	10^{-2}	23.0	26.7	24.9	23.6

wavelengths. However, when outages are allowed to occur with some small probability ($P_{outage}^{\max} > 0$), then CAC is particularly useful for increasing the teletraffic capacity and the maximum allowable offered load per free subscriber $r^{\max}$ if the OCDMA network is heavily loaded with high outage probabilities and therefore low teletraffic capacity (e.g. the systems in Fig. 4 with circuit activity $p > 60\%$).

However, when CAC introduces blocking into an OCDMA network, it is often the blocking constraint $P_{block}^{\max}$ that limits capacity. For example, in Table I when $P_{block}^{\max} \ll P_{outage}^{\max}$ the teletraffic capacities of the OCDMA network do not improve with CAC. As Fig. 5 illustrates, this happens because capacity is maximized when the network is operated with minimal blocking. It can be shown (for both CAC schemes) that the blocking constraint becomes the limiting factor approximately when $P_{block}^{\max} < P_{outage}^{\max}$. [7]

From Table I we see that the greatest increases in capacity due to CAC are obtained when $P_{block}^{\max} \gg P_{outage}^{\max}$, so that blocking new circuit requests reduces the outage probability and increases the capacity of the network before the blocking constraint becomes binding. For example, for the system described in Table I with $P_{block}^{\max} = 10^{-2}, P_{outage}^{\max} = 10^{-6}$, the teletraffic capacity of the OCDMA network improves by 16% with CS CAC, and by 8% with CIUCA CAC. Fig. 6 shows the how the teletraffic capacity a_c for this system varies as a function of different values of the blocking threshold B for each CAC scheme. From Fig. 6, the optimal blocking thresholds (*i.e.* B that achieves the maximum teletraffic capacity) for each CAC scheme are $B_{CS}^* = 35$ and $B_{CUICA}^* = 25$. Note that even in cases where the capacity of the WRN exceeds that of OCDMA (because $P_{block}^{\max} > P_{outage}^{\max}$) the capacity of OCDMA can always be made to equal (using a CS CAC scheme with $B^* = \Gamma$) or exceed that of a WRN (e.g. the OCDMA network with CS or CIUCA CAC in Fig. 6).

Furthermore, from Table I and Fig. 6, we observe that the

[7] To see why, consider the following approximations of equations (6) (8) (12) (13) for small r: for OCDMA with CS CAC, it is easy to verify that $P_{outage} \approx \binom{K}{\Gamma+1}(pr)^{\Gamma+1}$ and $P_{block} \approx \binom{K-1}{B} r^B$. Similarly, for OCDMA with CIUCA CAC, $P_{outage} \approx \binom{K}{\Gamma+1}(pr)^{\Gamma+1} \prod_{j=0}^{\Gamma} \beta_j$ and $P_{block} \approx 1 - \binom{K-1}{B} r^B \prod_{j=0}^{B} \beta_j$. For both CAC schemes, when $p < 1$ then P_{outage} is usually smaller than P_{block}, so that the blocking constraint is limiting approximately when $P_{block}^{\max} < P_{outage}^{\max}$.

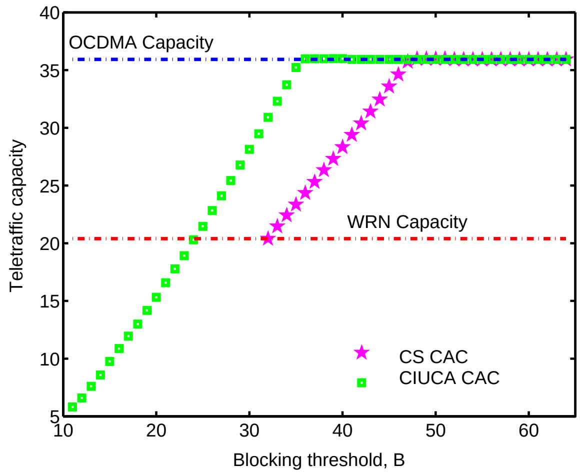


Fig. 5. A plot of teletraffic capacity a_c as a function of blocking threshold B for complete sharing CAC and CIUCA CAC. Horizontal lines represent the teletraffic capacities of a WRN and OCDMA without CAC. As in the fourth row of Table I, networks have $K = 64$ subscribers, $\Gamma = 32$ and circuit activity $p = 65\%$ and operating constraints $P_{outage}^{\max} = 10^{-2}$ and $P_{block}^{\max} = 10^{-3}$. In this situation it is optimal to operate the OCDMA network without CAC, since CAC does not bring any increases in teletraffic capacity.

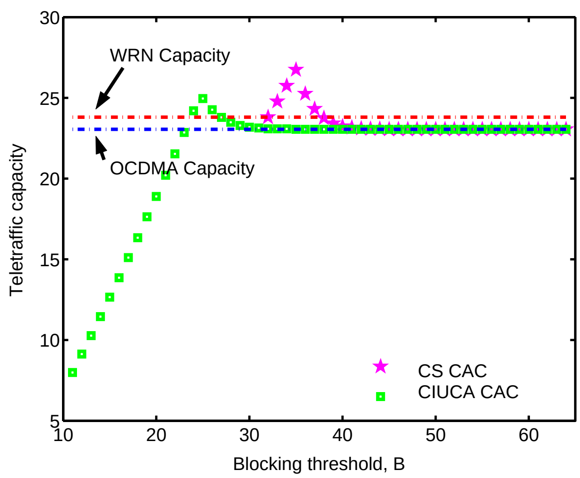


Fig. 6. Teletraffic capacity a_c as a function of blocking threshold B for complete sharing CAC and CIUCA CAC. This plot can be used to find the optimal value of the blocking threshold B^* for the CAC schemes. As in the last row of Table I, networks have $K = 64$ subscribers, $\Gamma = 32$ and circuit activity $p = 65\%$ and operating constraints $P_{outage}^{\max} = 10^{-6}$ and $P_{block}^{\max} = 10^{-2}$. The optimal blocking threshold is $B_{CS}^* = 35$ for complete sharing CAC and $B_{CIUCA}^* = 25$ for CIUCA CAC.

CS protocol is more effective in increasing teletraffic capacity than the CIUCA protocol. This is because the CS protocol is more effective in reducing outage probability; with the CS protocol, there are always fewer than $N = B$ circuit connections creating interference on the network, whereas with CIUCA the number of circuit connections can reach up to $N = K$. Now consider Table II, that shows how changes in p affect capacity a_c when the controller uses *non-optimal* blocking thresholds $B_{CS} = 35$ and $B_{CIUCA} = 25$ for each value of p. The blocking thresholds $B_{CS} = 35$ and $B_{CIUCA} = 25$ for CS and CIUCA CAC were found by optimizing each CAC controller for circuit activity $p = 65\%$. For the purpose of comparison, the table also shows the optimal blocking threshold, B^*, and corresponding optimal teletraffic capacities a_c^* for a CAC protocol optimized to each value of p. From Table II we can see that the optimal blocking threshold B^* of the CS protocol is more sensitive to changes in circuit activity p, than the optimal blocking threshold in a CIUCA protocol. Thus, if circuit activity on the network changes over time and the blocking thresholds are not varied accordingly, there can be a significant reduction in the capacity of an OCDMA network running CS CAC. The CIUCA protocol is more robust to changes in p. With CIUCA CAC, new circuit requests are blocked based on the number of *active* circuits M, so that the blocking condition $M \geq B$ adapts to fluctuations in circuit activity p. Meanwhile, the blocking condition for CS CAC, $N = B$, is independent of p. Therefore, while the CS protocol provides higher capacity, the CIUCA protocol is robust to fluctuations in p.

TABLE II

THE EFFECT OF CHANGES IN CIRCUIT ACTIVITY p ON TELETRAFFIC CAPACITY WHEN CAC CONTROLLERS ARE OPTIMIZED FOR $p = 65\%$ AND $K = 64, \Gamma = 32, P_{outage}^{\max} = 10^{-6}, P_{block}^{\max} = 10^{-2}$

	OCDMA	OCDMA CS-CAC			OCDMA CIUCA-CAC		
p %	a_c	B^*	a_c^*	a_c if $B = 35$	B^*	a_c^*	a_c if $B = 25$
90	16.6	32	23.6	16.6	27	21.0	18.8
80	18.6	32	23.6	19.3	25	23.6	20.9
70	21.3	34	25.3	23.4	25	23.6	23.7
65	**23.0**	**35**	**26.7**	**26.7**	**25**	**24.9**	**24.9**
60	25.0	36	27.5	26.6	25	26.2	26.2
50	30.0	41	31.6	26.6	24	30.8	30.6
40	37.4	47	38.7	26.6	24	37.9	37.6

We have seen throughout this paper that the average circuit activity p is a crucial parameter in the evaluations of OCDMA teletraffic capacity and the setting optimal blocking thresholds for the OCDMA CAC protocols. In the preceding analysis we have assumed circuit activity is a constant value for all subscribers. While this is a reasonable assumption for a traditional voice network [7], in a data network p typically varies with time. Then, the most conservative approach to dimension the network and the CAC controller is simply to use the largest possible value of p from the pool of subscribers. For better network utilization, an alternate approach could use centralized controller that pre-computes a tabulation of the optimal blocking threshold B^* for each value of p, and changes the blocking threshold as it detects changes in p according to the approximation $p \approx \frac{M}{N}$. Another option is to model p as a random variable with some known probability distribution, $f(p)$. Then the distribution of active circuits becomes

$$P[M = m] = \int_0^1 P[M = m|p] f(p) dp \qquad (15)$$

where $P[M = m|p]$ as in (4) for OCDMA, (7) for complete sharing CAC, etc. The distribution (15) can then be used to obtain the outage and blocking probabilities used to dimension the network and CAC controller. Furthermore, to improve estimates of the distribution of p, [23]'s Bayesian formulation may be used (see [23] Section III.B). That is, if p has some known prior distribution and we had a controller that measures N and M on the network at time t, to estimate the value of P_{outage} at future time $t+\epsilon$, the posterior distribution $f(p|N=n, M=m)$ can be used instead of $f(p)$ in (15).[8] A fully sequential Bayesian approach would repeatedly update the posterior distribution with each successive measurement. Finally, more sophisticated methods can be used to model data traffic (e.g. [26]'s model of an ON-OFF source with Pareto distributed ON and OFF time periods).

Moreover, in a heterogenous data network different subscribers have different values of p. Suppose that it is known that the network consists of K_c "class c" subscribers that utilize their circuits with activity variable p_c. In such cases, a class-based loss model may be used [9], [11]. We illustrate the approach for an OCDMA network without CAC. If $\mathcal{C}$ is set of subscriber classes, we define vectors $\mathbf{p}=(p_c; c\in\mathcal{C})$, $\mathbf{N}=(N_c; c\in\mathcal{C})$ and $\mathbf{M}=(M_c; c\in\mathcal{C})$ for activity, connected circuits and active circuits respectively. Then ([11] Thrm 6.2) we find that

$$P[\mathbf{N}=\mathbf{n}] = \prod_{c\in\mathcal{C}} \binom{K_c}{n_c} r^{n_c}(1+r)^{-K_c}$$

and using the approach in (4), it follows that

$$P[\mathbf{M}=\mathbf{m}|\mathbf{p}] = \prod_{c\in\mathcal{C}} \binom{K_c}{m_c} \alpha_c^{m_c}(1+\alpha_c)^{-K_c}$$

with $\alpha_c = p_c r/(1+(1-p_c)r)$. We can then find the outage probability from the distribution of $\mathbf{M}$ as

$$P_{outage} = \int P[\sum_{c\in\mathcal{C}} M_c > \Gamma|\mathbf{p}] f(\mathbf{p})\mathbf{dp}$$

IV. Conclusions

We have developed a framework for understanding the statistical-multiplexing properties and determining the teletraffic capacity of a circuit-switched OCDMA network carrying bursty data, where the cardinality of the CDMA spreading code is larger than the number of subscribers, each circuit is received with equal power, and performance is limited by MAI. In OCDMA, arriving circuit requests will always be accommodated by the network, while the BER of the other users on the network degrades gracefully. Thus, traditional blocking, which we modelled with the $G(K)/G/\Gamma(0)$ loss model for a circuit-switched WRN, is replaced for OCDMA with a $G(K)/G/\infty$ queuing model and an outage probability. An outage occurs when the number of actively transmitting circuits on an OCDMA network exceeds a outage threshold Γ such that all circuits experience an unacceptably degraded BER. We defined the teletraffic capacity as the maximum aggregate carried circuit load that can be accommodated by the network such that constraints on outage and blocking probabilities are satisfied.

We have compared an OCDMA network with outage threshold Γ to a WRN with the same number of subscribers and Γ wavelengths (see Figs. 3-4). We found that the teletraffic capacity of OCDMA exceeds that of a WRN in all cases, except when circuit activity p is very high while the outage constraints $P_{outage}^{\max}$ are much more stringent than the blocking constraints $P_{block}^{\max}$. Therefore, OCDMA is well suited to applications when conventional blocking is undesirable, and/or circuits carry bursty data. For example, for OCDMA and WRN with $K=64$ subscribers, $\Gamma=32$ with circuit activity $p=40\%$ as in voice systems (see Fig. 4), even when the constraint on outages is more stringent than the constraint on blocking ($P_{outage}^{\max}=10^{-6}$, $P_{block}^{\max}=10^{-2}$), the teletraffic capacity of OCDMA is about 37 connected circuits as compared to about 23 circuits for the WRN.

We have also studied the effect of two call admission control protocols on the capacity of the OCDMA network. With call admission control (CAC), the network blocks some new circuit requests in order to reduce the occurrence of outages. If outages are *never* allowed to occur ($P_{outage}^{\max}=0$), we showed how a CAC protocol that blocks new circuit requests when $N=\Gamma$ can be used so to match the capacity of the OCDMA network to that of a WRN. On the other hand, if outages are allowed to occur with some small probability ($P_{outage}^{\max}>0$), then CAC can be used to optimize the teletraffic capacity. We found that as long as circuit activity is low due to intermittent data transmission, or if the constraints on outages are weaker than the constraints on conventional blocking, then it is optimal to operate the OCDMA network as non-blocking system without CAC. Otherwise, when the constraints on outages are much stronger than the constraints on conventional blocking, we can use CAC protocols to increase the teletraffic capacity of the OCDMA network to match or exceed the capacity of a similar WRN. We studied two simple protocols, a complete-sharing (CS) CAC protocol that achieves larger increases in teletraffic capacity but is sensitive to changes in average circuit activity, and a check-interference-upon-call-arrival (CIUCA) CAC protocol that is robust to changes in circuit activity at the cost of smaller improvements in the capacity of the OCDMA network (see Tables I-II).

Our analysis has shown how statistical-multiplexing in circuit-switched OCDMA networks is achieved without the use of higher layer protocols. By exploiting this idea, and the fact that conventional blocking need not occur in OCDMA networks, we have shown how OCDMA can be an attractive optical multiple-access scheme for increasing the capacity of circuit-switched networks.

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[8]To obtain the posterior distribution $f(p|N=n, M=m)$ from the prior distribution $f(p)$ use $f(p|N=n, M=m) = \frac{f(p)P[M=m|N=n,p]}{\int_0^1 P[M=m|N=n,p]f(p)dp}$.

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Appendix

K	Number of subscribers
ν	Average arrival rate of new circuit requests per subscriber
$\frac{1}{\mu}$	Average circuit holding time
$r = \frac{\nu}{\mu}$	Offered circuit load per free subscriber
p	Average circuit activity
N	Number of circuit connections
M	Number of actively transmitting circuit connections
Γ	OCDMA outage threshold / number of wavelengths in WRN
B	OCDMA call admission control blocking threshold
a	Aggregate offered circuit load, $K\frac{r}{r+1}$
a_c	Aggregate carried circuit load, $E[N]$
P_{outage}	Outage probability
P_{block}	Blocking probability
$P_{outage}^{\max}$	Outage constraint (Maximum allowable outage probability)
$P_{block}^{\max}$	Blocking constraint (Maximum allowable blocking probability)

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