Multi-class/Multi-rate Overlapped Optical FFH-CDMA System: SIR Performance Evaluation And Cutoff Rates Analysis

Elie Inaty
Dept. of Computer Eng.
University of Balamand, Lebanon
e-mail: elie.inaty@balamand.edu.lb

Hossam M. H. Shalaby
Dept. of Electrical Eng.
University of Alexandria, Egypt
e-mail: shalaby@ieee.org

Paul Fortier
Dept. of Electrical Eng.
Laval University, Canada
e-mail: fortier@gel.ulaval.ca

Abstract—**We consider an optical CDMA network that supports multiple traffic classes. Each class has different processing gain (PG) and performance requirements. In this paper, we generalize the method that we have previously proposed to analyze the cutoff rates for a single-class multirate optical frequency hopping code division multiple access system (OFFH-CDMA), to the case of multi-class multirate OFFH-CDMA system. This approach exploits the linear structure of passive optical CDMA systems and the nominal time required to accomplish the encoding-decoding operations in such systems. A system model is presented and analyzed based on a newly introduced bit-overlap procedure. An expression that relates the cutoff rates of the offered classes is introduced and it is termed the service curve. It is shown that for a required quality of service (QoS) guarantee, a number of active users, and a given probability of hit, the system's data rates can be increased beyond the nominal limits imposed by the physical constraint of the encoder-decoder sets.**

Keywords-Overlapping coefficient, Cutoff rate, Service Curve.

I. INTRODUCTION

Due to the emerging demand for variable and hierarchical quality of service (QoS) optical fiber communication networks for multimedia applications, future optical services will likely integrate many different streams of traffic [1][3]. For this reason, integration of heterogeneous traffic with different transmission rates and QoS requirements in optical code division multiple access (CDMA) has received much attention lately [1]-[5].

A new method has been proposed in [8] to analyze the cutoff rate of a single class variable-bit-rate (VBR) OFFH-CDMA system. A system model was presented and analyzed based on a newly introduced bit-overlap procedure. An expression for the cutoff rate was also derived. It was shown that, the single-class system's data rate could be increased beyond the nominal limit imposed by the physical constraint of the encoder-decoder set. Thus, the system is known as overlapped OFFH-CDMA system.

In this work, we generalize the problem considered in [8] from a single-class system to a multi-class one. Each class is characterized by a given PG and a QoS requirement. Due to the fact that the cutoff rates of the classes are correlated, we will not be able to obtain an expression for the cutoff rate in each class. Instead, we will obtain an acceptance region, the boundary of which represents the maximum transmission rates in all the classes.

Following the introduction, the paper is organized as follows. Section II presents the system model. In Section III, we describe a closed form solution for the average variance of the multiple access interference MAI and the signal to interference ratio (SIR), and we quantify the effective increase in the number of hits as a function of the transmission rate. In Section IV, a service curve is introduced and derived, which relates the cutoff rates of the offered multimedia classes in a multi-class system. Section V contains numerical results and discussions. Finally, the conclusion is presented in Section VI.

II. MULTI-CLASS SYSTEM MODEL

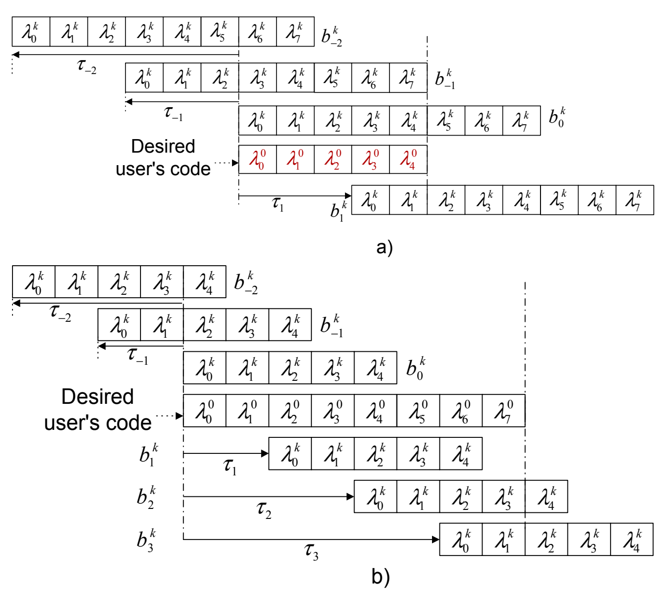

Fig. 1: Overlapped codding scheme.

Consider a multirate OFFH-CDMA communication network that supports M users in N different classes, which share the same optical medium in a star architecture [5]. The corresponding PGs for each class are given by

$G_0 > G_1 > ... > G_{N\text{-}1}$. The encoding and decoding are achieved passively using a sequence of fiber Bragg gratings. The gratings will spectrally and temporally slice an incoming broadband pulse into several components equally spaced at chip intervals $T_c = 2n_g L_c / c$ [5][6]. L_c represents the grating length assuming that the grating's temporal response is an ideal square wave function, c is the speed of light, and n_g is the group index. The chip duration, and the number of gratings will establish the nominal bit rate of the system, *i.e.* the round trip time of light, from a given transmitted bit, to be totally reflected from the encoder. This nominal bit duration in a structure of G_s gratings is given by $T_s = 2G_s n_g L_c / c$, which is normally greater or equal to the transmission bit time period T_{b_s}. The corresponding nominal rate is $R_{n\_s} = 1/T_s$.

Due to the linearity of the gratings (first in first out FIFO), hence the linearity of the encoder-decoder set, when the data rate increases beyond R_{n_s}, multi-bits will be coded during the time period T_s and transmitted as revealed in Fig. 1. At a given receiver the decoder observes practically multicode, which are delayed according to the transmission rate of the source as shown in Fig. 1. When user k transmits using rate $R_s > R_{n\_s}$, it introduces a bit overlap coefficient ε_s according to which the new rate is related to the nominal rate through the following equation

$$R_s = \frac{G_s}{G_s - \varepsilon_s} R_{n\_s} \quad (1)$$

In this paper we assume 1) a chip synchronous system and a discrete rate variation, 2) all users in the *class-s*, $s \in \{0,1,...,N-1\}$, have the same bit overlap coefficient $0 \le \varepsilon_s < G_s - 1$, thus each class is characterized by $(G_s, \varepsilon_s, \beta_s)$, where β_s is the QoS requirement representing a lower bound on the class's SIR, and 3) a unit transmission power for all the users.

A. Signal Structure

We define $a_k^{(s)}(t,f)$ and $b_k^{(s)}(t)$ as the hopping pattern and the baseband signal, respectively, where t and f represent the time and frequency dimensions. From Fig. 1, the optical bit stream can be seen to be serial-to parallel converted to v optical pulses. Assuming that the desired user is using the *class-m*, which is characterized by a PG G_m and an overlapping coefficient ε_m. Because the bit b_X^k from the v-bits is delayed by $\tau_X = X(G_s - \varepsilon_s)T_c$, this suggests that the channel model, as seen by the desired receiver, can be represented as a tapped delay line with tap spacing of $\tau_{-1} = -(G_s - \varepsilon_s)T_c$ from left and $\tau_1 = (G_s - \varepsilon_s)T_c$ from right. The tap weight coefficients $b_X^k \in \{0,1\}$ depending on whether the transmitted bit is zero or one. The truncated tapped delay line model as seen by the desired receiver is shown in Fig. 2. Accordingly the transmitted signal is given by

$$S_k(t,f) = \sum_v b_v^k a_k^{(s)}(t - \tau_v, f) \quad (2)$$

We define v and τ_v as the index of the overlapping bit and its associated time delay, respectively.

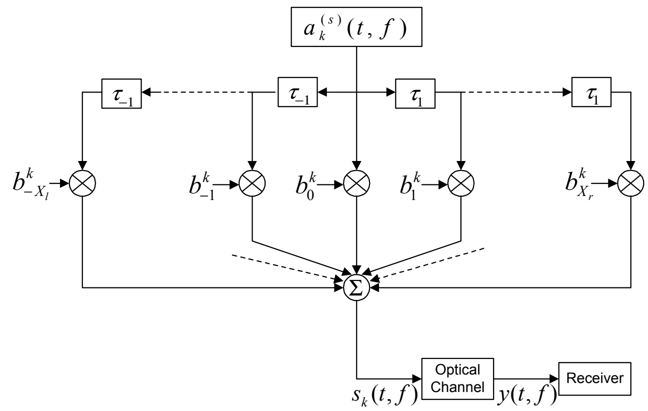

Fig. 2: Channel model.

Lemma 1: *Given an interferer k with* (G_s, ε_s) *and the desired user with* (G_m, ε_m) $\forall s,m \in \{0,1,...,N-1\}$. *At the desired receiver end, during the nominal time period* T_m, *the observed total number of taps in channel k is given by*

$$N_k(G_m, G_s, \varepsilon_s) = \left\lceil \frac{\varepsilon_s}{G_s - \varepsilon_s} \right\rceil + \left\lceil \frac{\Delta G + \varepsilon_s}{G_s - \varepsilon_s} \right\rceil + 1 \quad (3)$$

where $\lceil x \rceil$ *is the smallest integer greater than x and* $\Delta G = G_m - G_s$.

Proof: For a given rate R_s corresponding to $0 \le \varepsilon_s \le G_s - 1$ through (1) we can notice that in order for any transmitted bit b_X^k not to correlate with the desired user code during the time period T_m, the following inequalities must be satisfied

1) *Preceding bits from the right*

$$X \ge \frac{G_m}{G_s - \varepsilon_s} \quad (4)$$

If we use the fact that we consider discrete chip overlap, the smallest integer that satisfies (4) is

$$X = \left\lceil \frac{G_m}{G_s - \varepsilon_s} \right\rceil$$

Thus, we can define the final bit $b_{X_r}^k$ that correlates with the desired decoder from the right as follows

$$X_r = \left\lceil \frac{G_m}{G_s - \varepsilon_s} \right\rceil - 1 = \left\lceil \frac{G_m - G_s + \varepsilon_s}{G_s - \varepsilon_s} \right\rceil = \left\lceil \frac{\Delta G + \varepsilon_s}{G_s - \varepsilon_s} \right\rceil$$

2) *Upcoming bits from the left*

The same analysis can be applied for the upcoming bits but with the following inequality that must be satisfied

$$X \geq \frac{G_s}{G_s - \varepsilon_s} \quad (5)$$

The smallest integer that satisfies (5) is

$$X = \left\lceil \frac{G_s}{G_s - \varepsilon_s} \right\rceil$$

Therefore, the final bit $b_{X_l}^k$ that correlates with the desired decoder from left is given by

$$X_l = \left\lceil \frac{G_s}{G_s - \varepsilon_s} \right\rceil - 1 = \left\lceil \frac{\varepsilon_s}{G_s - \varepsilon_s} \right\rceil$$

Hence, the total number of observed transmitted codes is equal to X_r plus X_l in addition to the normal bit b_0^k, which proves (3). ■

Lemma 2: *Given an interferer k with* (G_s, ε_s) *and the desired user with* (G_m, ε_m)*, the observed total number of transmitted codes from transmitter k that undergo a total overlap with the desired correlator during the nominal time period* T_m *and excluding the normal bit* b_0^k*, is given by*

$$X_t = \left\lfloor \frac{|\Delta G|}{G_s - \varepsilon_s} \right\rfloor \quad (6)$$

where $\lfloor x \rfloor$ *is the highest integer smaller than x and* $|\Delta G|$ *is given by*

$$|\Delta G| = \begin{cases} G_m - G_s, & \text{if } G_m > G_s \\ G_s - G_m, & \text{if } G_m \leq G_s \end{cases} \quad (7)$$

Proof: omitted due the lake of permitted space. ■

The received signal at the input of the decoder is therefore given by

$$y(t,f) = n(t) + \sum_{k=0}^{M-1} \sum_{v=-X_l}^{X_r} b_v^k a_k^{(s)}(t - \tau_v, f)$$

where $n(t)$ is an additive white Gaussian noise (AWGN) with two-sided power spectral density $\Gamma_0/2$.

B. Decoder's Output

Without loss of generality, we assume that the correlation-matched filter is matched to the zeroth signal with class-m. The output of the noncoherent matched filter correlator will be

$$Z_0^{(m)} = \Gamma + \int_0^{T_m} \sum_{k=0}^{M-1} S_k(t - \tau_v, f) a_0^{(m)}(t,f) dt$$

where Γ is a zero-mean AWGN with variance $\sigma_n^2 = \Gamma_0 T_m / 4$. The MAI I_k from user k that transmits data with rate R_s can be written as

$$\begin{aligned} I_k = & \sum_{v=-X_l}^{-1} \int_0^{\tau_v} b_v^k h\left(a_k^{(s)}(t-\tau_v), a_0^{(m)}(t)\right) dt \\ & + \sum_{v=0}^{X_t} \int_{\tau_v}^{\tau_v + T_s} b_v^k h\left(a_k^{(s)}(t-\tau_v), a_0^{(m)}(t)\right) dt \\ & + \sum_{v=X_t+1}^{X_r} \int_{\tau_v}^{T_m} b_v^k h\left(a_k^{(s)}(t-\tau_v), a_0^{(m)}(t)\right) dt, \quad G_m > G_s \end{aligned} \quad (8)$$

and

$$\begin{aligned} I_k = & \sum_{v=-X_l}^{1-X_t} \int_0^{\tau_v} b_v^k h\left(a_k^{(s)}(t-\tau_v), a_0^{(m)}(t)\right) dt \\ & + \sum_{v=-X_t}^{0} \int_0^{T_m} b_v^k h\left(a_k^{(s)}(t-\tau_v), a_0^{(m)}(t)\right) dt \\ & + \sum_{v=1}^{X_r} \int_{\tau_v}^{T_m} b_v^k h\left(a_k^{(s)}(t-\tau_v), a_0^{(m)}(t)\right) dt, \quad G_m \leq G_s \end{aligned} \quad (9)$$

$\forall\ k \neq 0$. $h(.)$ is the Hamming function [7]. The sequences $a_k^{(s)}(t)$ and $a_0^{(m)}(t)$ are numbers representing wavelengths used at time t for the k^{th} interferer and the desired user, respectively. Notice that $a_k^{(s)}(i) = a_k^{(s)}(i + T_s)$. In addition, in [8] we have defined a new performance parameter called the auto-interference, I_0, caused by the desired user's signal and it was shown to be zero for one coincidence sequences [9][10]. This also apply in this paper, thus we can write

$$I_0 = 0 \quad (10)$$

III. SIR Performance Evaluation

Since the user may set a connection for a particular multimedia class and modify it dynamically, the index s is a discrete random variable with a certain prior probability

$$p_k^{(i)} = \Pr(\text{user } k \text{ chooses class-}i) = \Pr(s = i) \quad \forall\, i \in \{0, 1, ..., N-1\} \quad (11)$$

with $\sum_{s=0}^{N-1} p_k^{(s)} = 1$ and we call $p_k^{(s)}$ the multimedia probability mass function (pmf) for user k. I_k, $\forall\ 0 \leq k \leq M-1$, is assumed to be an independent random variable. Hence, the variance of the decision variable $Z_0^{(m)}$ is

$$\text{var}\left[Z_0^{(m)}\right] = \sum_{k=1}^{M-1} \sum_{s=0}^{N-1} p_k^{(s)} \sigma_{I_k/s}^2 + \sigma_n^2 \quad (12)$$

$\sigma_{I_k/s}^2$ represents the interference power caused by an active user k using class-s and it is given by

$$\sigma_{I_k}^2 = E(I_k^2) - E^2(I_k) \quad (13)$$

where $E(.)$ is the expectation operator over all possible values of the overlapping bits b_X^k for $X \in \{-X_l, ..., X_r\}$ assuming that $\Pr(b_X^k = 1) = \Pr(b_X^k = 0) = 1/2$. Using the Frequency Shifted Version (FSV) system proposed in [6], $E(I_k / s)$ can be made equal to zero and the cross terms generated from squaring the summation in $E(I_k^2 / s)$ become zeros, which enables us to write

$$E\left(I_k^2/s\right)=\Re_k\left(T_m,T_s,\varepsilon_s\right)=$$

$$\begin{cases}\frac{1}{2}\left[\begin{array}{l}\sum_{v=-X_l}^{-1}H_{k,0}^2\left(0,\tau_v\right)+\sum_{v=0}^{X_t}H_{k,0}^2\left(\tau_v,\tau_v+T_s\right)\\+\sum_{v=X_t+1}^{X_r}H_{k,0}^2\left(\tau_v,T_m\right)\end{array}\right], & G_m>G_s\\ \frac{1}{2}\left[\begin{array}{l}\sum_{v=-X_l}^{1-X_t}H_{k,0}^2\left(0,\tau_v\right)+\sum_{v=-X_t}^{0}H_{k,0}^2\left(0,T_m\right)\\+\sum_{v=1}^{X_r}H_{k,0}^2\left(\tau_v,T_m\right)\end{array}\right], & G_m\le G_s\end{cases} \tag{14}$$

where, $H_{k,0}\left(\tau_i,\tau_j\right)=\int_{\tau_i}^{\tau_j}h\left(a_k\left(t-\tau_v\right),a_0\left(t\right)\right)dt$ (15)

Let $q_v=\tau_v/T_c$, we can write

$$H_{k,0}(0,\tau_v)=T_cH_v(0,q_v)=T_c\sum_{j=0}^{q_v-1}h(a_{j-q_v}^k,a_j^0) \tag{16}$$

$$H_{k,0}\left(\tau_v,T_m\right)=T_cH_v\left(q_v,G_m\right)=T_c\sum_{j=q_v}^{G_m-1}h\left(a_{j-q_v}^k,a_j^0\right) \tag{17}$$

$$\begin{aligned}H_{k,0}\left(\tau_v,\tau_v+T_s\right)&=T_cH_v\left(q_v,q_v+G_s\right)\\&=T_c\sum_{j=q_v}^{q_v+G_s-1}h\left(a_{j-q_v}^k,a_j^0\right)\end{aligned} \tag{18}$$

Using (16)-(18), $\Re_k\left(T_m,T_s,\varepsilon_s\right)$ can be written as

$$\Re_k\left(T_m,T_s,\varepsilon_s\right)=$$

$$\begin{cases}\frac{T_c^2}{2}\left[\begin{array}{l}\sum_{v=-X_l}^{-1}H_v^2\left(0,q_v\right)+\sum_{v=0}^{X_t}H_v^2\left(q_v,q_v+G_s\right)\\+\sum_{v=X_t+1}^{X_r}H_v^2\left(q_v,G_m\right)\end{array}\right], & G_m>G_s\\ \frac{T_c^2}{2}\left[\begin{array}{l}\sum_{v=-X_l}^{1-X_t}H_v^2\left(0,q_v\right)+\sum_{v=-X_t}^{0}H_v^2\left(0,G_m\right)\\+\sum_{v=1}^{X_r}H_v^2\left(q_v,G_m\right)\end{array}\right], & G_m\le G_s\end{cases} \tag{19}$$

If we define $\Re_k\left(G_m,G_s,\varepsilon_s\right)=\Re_k\left(T_m,T_s,\varepsilon_s\right)/\left(T_c^2/2\right)$, then we substitute into (13), the SIR experienced by any active user that uses class-*m* is

$$\mathrm{SIR}_m=\frac{G_m^2}{\sum_{k=1}^{M-1}\sum_{s=0}^{N-1}p_k^{(s)}\Re_k\left(G_m,G_s,\varepsilon_s\right)+\sigma_n^2} \tag{20}$$

A. Effective Increase in the Number of Hits

***Proposition 1*:** For one-coincidence sequences with non-repeating frequencies [9], the expected value of the increase in the number of hits caused by any active interferer with $\left(G_s,\varepsilon_s\right)$ on a desired user with $\left(G_m,\varepsilon_m\right)$ is given by

$$\begin{aligned}I_H^k\left(G_m,G_s,\varepsilon_s\right)=\frac{1}{F}\Bigg[&\left(G_s-\frac{\left(G_s-\varepsilon_s\right)}{2}\right)X_l-\frac{\left(G_s-\varepsilon_s\right)}{2}X_l^2\\&+\left(G_m-\frac{\left(G_s-\varepsilon_s\right)}{2}\right)X_r-\frac{\left(G_s-\varepsilon_s\right)}{2}X_r^2\\&+\left(\frac{\left(G_s-\varepsilon_s\right)}{2}-\left|\Delta G\right|\right)X_t+\frac{\left(G_s-\varepsilon_s\right)}{2}X_t^2\Bigg]\end{aligned} \tag{22}$$

where X_r, X_l, X_t, and $\left|\Delta G\right|$ are given throughout Lemma 1 and Lemma 2 and *F* is the total number of available frequencies.

***Proof*:** Is omitted due the lake of permitted space. ■

B. Average SIR

Assuming that the overlapping codes are independent virtual active users and one-coincidence sequences, we can compute the average correlation given in (19). In addition, if we assume that the multimedia pmf is the same for every user, $p_k^{(s)}=p^{(s)}$, the average SIR for the desired user with $\left(G_m,\varepsilon_m\right)$ will be

$$\mathrm{SIR}_m=\frac{G_m^2}{\frac{(M-1)}{2}\cdot\sum_{s=0}^{N-1}\left[\frac{p^{(s)}\cdot G_s}{F}+p^{(s)}\cdot I_H^k\right]+\sigma_n^2} \tag{23}$$

IV. Cutoff Rates Analysis

The main objective of this part is to analyze the cutoff rate for each working class in the system given *M*, G_s, $p^{(s)}$, and the QoS guarantee β_s for every $s\in\{0,1,...,N-1\}$. For the clarity of the method and for mathematical convenience, we will present the case of a two-class system. In addition, we assume that all the classes have the same PG $\left(G_s=G\right)$. In this case, $X_l=X_r=X=\left\lceil\frac{\varepsilon_s}{G-\varepsilon_s}\right\rceil$. Therefore, (22) is simplified to

$$I_H^k\left(G,\varepsilon_s\right)=\frac{1}{F}\left[\left(G+\varepsilon_s\right)X-\left(G-\varepsilon_s\right)X^2\right] \tag{24}$$

Knowing that *X* is bounded by

$$\frac{\varepsilon_s}{G-\varepsilon_s}\le X=\left\lceil\frac{\varepsilon_s}{G-\varepsilon_s}\right\rceil\le\frac{G}{G-\varepsilon_s}$$

the value of $I_H^k\left(G,\varepsilon_s\right)$ is simplified to

$$I_H^k\left(G,\varepsilon_s\right)=\frac{G}{F}\left(\frac{\varepsilon_s}{G-\varepsilon_s}\right) \tag{25}$$

Using (25) in (23) we obtain

$$\mathrm{SIR_m}=\frac{G^2}{\frac{G^2\left(M-1\right)}{2F}\cdot\sum_{s=0}^{N-1}\left[\frac{p^{(s)}}{G-\varepsilon_s}\right]+\sigma_n^2} \tag{26}$$

Consider a two-class system namely *class*-0 and *class*-1, which are characterized by $\left(\varepsilon_0,\beta_0\right)$ and $\left(\varepsilon_1,\beta_1\right)$. By means of the above results and taking $\text{SIR}_0 \geq \beta_0$ and $\text{SIR}_1 \geq \beta_1$ and neglecting the effect of σ_n^2, we obtain

$$\left(G - p^{(1)}\right)\varepsilon_0 + \left(G - p^{(0)}\right)\varepsilon_1 - \varepsilon_0\varepsilon_1 \leq \frac{2FG^2}{(M-1)} - G \cdot \max\{\beta_0, \beta_1\} \tag{27}$$

Equation (27) draws the overlapping region of the system, meaning the region under which we can increase ε_0 and ε_1 without violating the QoS requirements β_0 and β_1. This line is called the *service curve* of the system.

V. Numerical Results

Using EHC family of codes [9] and using $F = 41$ available frequencies with $G = 40$, Fig. 3 plots the SIR for an active user while varying its normalized transmission rate and for different values of the number of users. It is worthwhile to mention that the rate is normalized in the sense that it represents the percentage increase in the transmission rate with respect to the nominal rate R_{n_s} obtained without overlap. Notice that as the normalized transmission rate increases (or equivalently the overlapping coefficient increases), the SIR decreases.

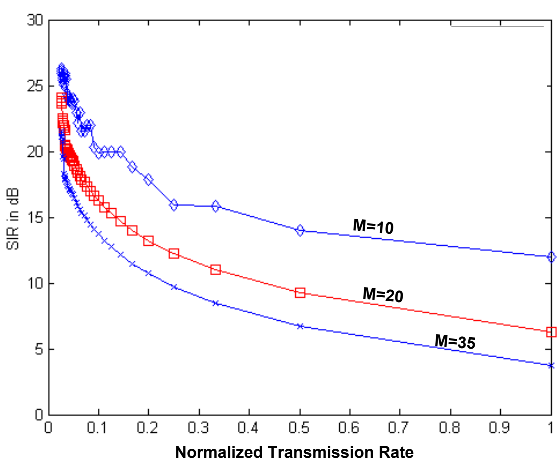

Fig. 3: Average SIR versus the normalized transmission rate.

Now we discuss the cutoff rates of a two-class case with $G_0 = 40$ and $G_1 = 20$. Our focus is on the service curve and its dependence on the system parameters. Fig. 4 shows ε_1 versus ε_0, which corresponds to the service curve, when we vary β_1 and fix $\beta_0 = 210$, $F = 80$, $M = 20$, and $P^{(0)} = P^{(1)} = 0.5$. It is clear that when $\beta_1 > 110$, the system does not allow overlap in either classes. As β_1 decreases, the overlapping region becomes wider and the system allows more overlap for the two classes. The case $\beta_1 = 80$ represents the limiting condition; in the sense that further decreasing β_1 will not increase the overlapping region due to the fact that only the condition on β_0 will affect this region.

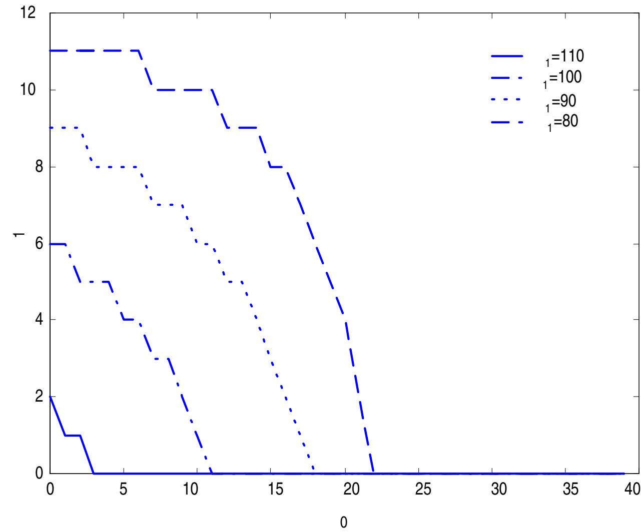

Fig. 4: ε_1 versus ε_0 when we very β_1 and fixing $\beta_0 = 210$, $F = 80$, $M = 20$, and the multimedia pdf $P^{(0)} = P^{(1)} = 0.5$.

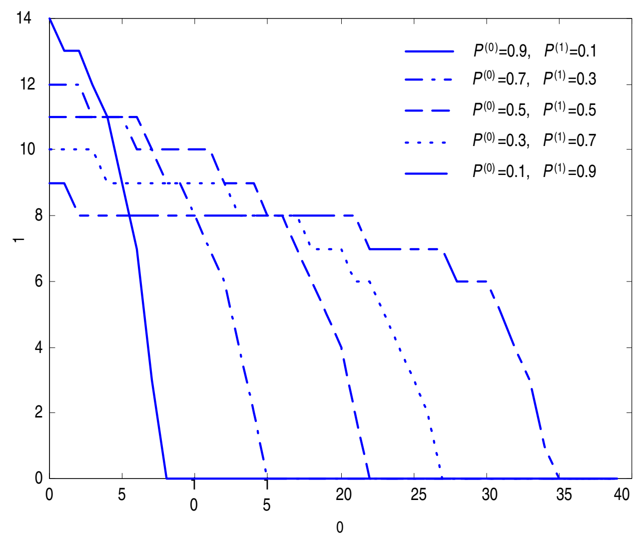

Fig. 5: ε_1 versus ε_0 when we very the multimedia pdf and fixing $F = 80$, $\beta_0 = 210$, $\beta_1 = 90$, and $K = 20$.

On the other hand, Fig. 5 plots the service curve when varying the multimedia pdf $P^{(s)}$ while fixing $F = 80$, $\beta_0 = 210$, $\beta_1 = 90$, and $M = 20$. The important thing to notice in this figure is that when $P^{(0)} > P^{(1)}$, the system allows more relative overlap for *class*-1. As $P^{(0)} < P^{(1)}$, more relative overlap is allowed for *class*-0. In Fig. 6, the effect of F is emphasized. As F becomes large, the overlapping region tends asymptotically to a rectangle bounded by G_1 and G_0. Therefore, full overlap is allowed for the two classes.

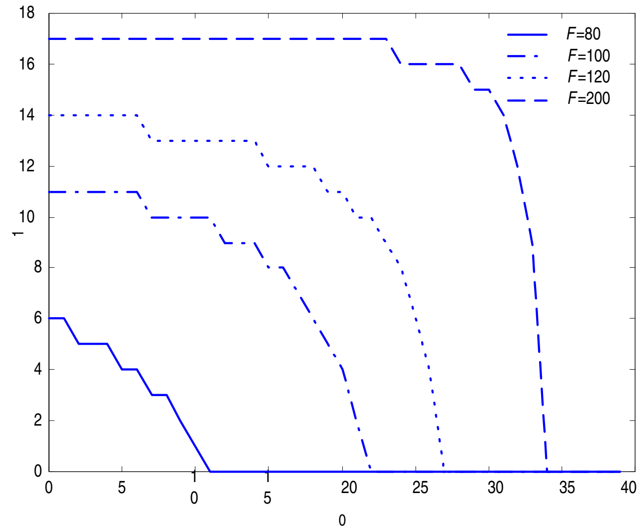

Fig. 6: ε_1 versus ε_0 when we very F and fixing $\beta_0 = 210$ and $\beta_1 = 100$, $K = 20$, $P^{(0)} = P^{(1)} = 0.5$.

VI. Conclusion

In this paper, we have extended our previous analytical derivations from a single class system to a multi-class one. A system model was presented and the SIR was derived. In addition, we have been able to obtain a service curve based on which the cutoff rates for a multi-class system was analyzed. Simulation and analytical results showed that it is possible to increase the transmission rate well beyond the nominal rate imposed by the physical dimensions of the encoder/decoder pairs. Thus, the overlapped OFFH-CDMA can be a good candidate for multirate/multimedia applications.

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