

DECLARATION

I declare that no part of the work referred to in this thesis has been submitted in support of an application for another degree or qualification from this or any other University or Institution.

ABSTRACT

In this thesis, an overview on optical code division multiple access (**OCDMA**) communication systems is presented. Focus is oriented towards random access protocols and media access control (**MAC**) protocols for future optical CDMA networks.

A link layer protocol that supports multi-rate on (**OCDMA**) network is proposed based on multi-coding techniques to improve the performance of the network. The main objective is to allow users of different data rates to access the network simultaneously without affecting or reducing the networks performance.

Signature sequences are achieved using one-coincidence frequency hop code/optical orthogonal code (**OCFHC/OOC**) 2D codes which slightly increase the performance than **OOC**. Two different link layer protocols are considered in the analysis. In the first protocol, a signature code is only assigned to a single user. In the second protocol, however, a signature code is permitted to be assigned to several users after being cyclic shifted randomly. The system overall throughput and average packet delay are derived for two receiver models; namely, the correlation and chip level receivers. In the analysis, the effect of multiple access interference (**MAI**), the receiver shot and thermal noise are taken. The network users are classified into two classes with two different transmission rates which are 1 and 2 Codes/User for single and multi-rate class, respectively. Results reveal that, the proposed multi-rate network outperforms the traditional single rate network in terms of both average throughput and packet delay.

Furthermore, number of classes is generalized. Thus, the performance of the network is even better. In conclusion, proposed network not only allows users demanding different rates to transmit their data reliably but also improves the overall performance.

SUMMARY

Due to the vast bandwidth offered by the optical fibers and the extra-high optical signal processing speed bestowed by the optical components, optical code-division-multiple-access (**OCDMA**) techniques have been given an increasing interest in the last decade. In addition, **OCDMA** technique has several advantages over other multiple access techniques, such as unnecessary time synchronization, frequency management, simple communication protocols, complete utilization of the entire time-frequency domain by each subscriber, flexibility in network design, and security against interception [1]. According to studies by Stok and Sargent, CDMA can offer a higher capacity than wavelength division multiple access (**WDMA**) for local area networks if noise is neglected. Furthermore, **CDMA** can be efficiently used in conjunction with **WDMA** on multimedia communication networks where multiple services with different traffic requirements are to be integrated. However, when shot noise and thermal noise are taken into consideration, **CDMA** is much more sensitive to the signal to noise ratio than **WDMA** [2]. Therefore, it is not clear that the comparison will hold when also other noise types are taken into account.

Optical fibers have a huge transmission capacity. On the other hand, optical technology is still in its infancy, and conversions between electrical and optical environment are relatively slow compared to the transmission capacity. Thus, in optical networks the processing power, instead of bandwidth, is the limiting factor. Therefore, the requirements for the media access control (**MAC**) protocols are different in the optical network than in the traditional electronic network. In this work, we have focused mainly on two random access protocols for multi-rate **OCDMA** networks. In Pro 1, assuming that all codes are available in a pool, when a user wants to transmit a packet to a receiver, it is assigned a code at random. This code is then removed from the pool and is no longer available for further assignment during a slot. In Pro 2, it is similar to Pro 1 but the codes are never removed from the pool. That is, any active user can always find a code to transmit its data. Of course, more interference is possible in this case since a code can be used more than once. However, the offered traffic (at a given time slot) might be higher than the previous case. In order to reduce the probability of interference among different users, a code is randomly cyclic shifted around itself once selected [3].

Several receiver detection models have been proposed in our thesis, the most traditional ones are the correlation receiver [4], correlation receiver with double hard limiters [5], and chip-level receiver [6]. The main difference between the correlation receivers and chip-level

receivers is that in the latter, the bit decision rule depends on the received optical power in each mark chip of the signature code, whereas in the former, it depends on the total optical power in all underlined mark chips.

In optical **CDMA** techniques, a user is normally given a signature code that satisfies good auto- and cross-correlation properties [7, 8] to help in its data transmission and identifying itself. In this work, we adopt two-dimensional optical orthogonal codes to extend the cardinality to a larger set, where Multi-coding technique support several kinds of data with different bit rates, where each user is assigned a set of sequence codes.

Two-dimensional optical orthogonal code (**2-D OOC**), which extends the cardinality while still possessing good auto-and-cross correlation properties, is proposed by introducing another dimension (wavelength) based on 1-D OOC. A 2-D OOC codeword is represented by a $M_1 \times M_2$ matrix consisting of 0 and 1, where M_1 is the number of wavelengths used, and M_2 is the code length (i.e., the number of time slots used). Several 2-D OOCs have been constructed by employing different wavelength-hopping and time-spreading patterns. A 2-D OOC, OCFHC/OOC with ideal properties has been used where OCFHC/OOC takes the advantages of **OCFHC** and **OOC** to possess excellent correlation properties, and its cardinality achieves the upper bound theoretically; namely, OCFHC/OOC is an optimal 2-D OOC.

Owing to the increasing interest in the multi-media applications, networks supporting heterogeneous traffic, e.g., high and low-speed data, text, image, audio, and video with varieties of quality of service and traffic requirements, have become indispensable. Various techniques have been proposed for the support of multi-rate services provision in **OCDMA** networks. Varying the code length [9, 10], adopting optical fast frequency hopping [11], and multi-coding schemes are the most popular techniques employed to provide multi-rate service in OCDMA networks.

Providentially, multi-coding techniques have been introduced in [12] for optical code-division multiple-access (**OCDMA**) systems. In these techniques, traffic streams with different transmission rates are integrated into a unified architecture. Users of high rates are assigned a number of codes based on the relation between the rates they are requesting and the basic rate of the system.

In this thesis, multi-rate on optical code division multiple access (OCDMA) network based on multi-coding techniques is applied and studied the performance of the network. Two different link layer protocols are modified in the analysis.

The objective is to allow users of different data rates to access the network simultaneously without affecting or reducing the networks performance. The performance of these

protocols is evaluated the average system (or network) throughput in packets per slot, which tells how many packets on the average are received successfully per time slot. The other one is the average packet delay in time slots, which tells after how many slots (from transmission) on the average a packet will be received successfully. Most studies of optical **CDMA** use simple channel models where noise is neglected. One of the main objectives of this thesis was to study a model where both shot and thermal noise, are taken into account and see how they can effect in the overall system performance. Total system throughput and average packet delay have been derived where the performance has been also examined for both correlation and chip-level receivers.

Furthermore, the aforementioned performance measures are evaluated numerically for both two-class and general-class networks under several design parameters. The results are compared to the case of single-class networks which reveal that, the multi-rate network performs better than a single-rate network under the developed protocols.

SYMBOLS

A	User activity
b	Bit value zero or one
$ C $	Cardinality of OOCs
$C_{OOC} = \{a_1, a_2, \dots, a_{ C }\}$	Set of direct sequence OOCs
d	Average delay time spent in the backlog mode
d_{min}	Minimum distance of OOCs
D	System average packet delay
e	Electron charge
F	APD excess noise factor
G	Processing gain
G_V	Variable processing gain
G_{APD}	Average APD gain
H_{max}	Maximum correlation between two OCFHC codewords
I_d	APD dark current
k	Positive integer
K	Number of bits in a packet
k_B	Boltzmann's constant
k_{eff}	APD effective ionization ratio
L	Code length
m_1	Number of Codes/User in class 1
m_{bi}	Conditional mean of the decision variable Y_i
m_x	Number of Codes/User in class x
n_1	Number of backlogged user in class 1
n_2	Number of backlogged user in class 2
n_x	Number of backlogged user in class x
N	Number of users in system

N_{ooc}	OOO code length
N_1	Number of users in class 1
N_2	Number of users in class 2
N_x	Number of users in class x
p	Prime number
p_1	Probability of 1 chip-interference
p^k	Number of available wavelenghts
p_w	Probability of w chip-interference
P_{av}	Received average peak laser power
P_{bc}	Conditional bit correct probability
P_{bl}	Probability of backlogged users
P_{th}	Probability of thinking users
P_{in}	Input power of optical hard-limiter
P_{nm}	Transition probability of backlogged users from state n to state m
P_{out}	Output power of optical hard-limiter
P_s	Packet success probability
q	Average number of “hit”s between two codewords
Q	Average received photons per pulse
Q_f	Number of available frequencies
Q_d	Photon count due to dark current within a chip interval
r	Number of active users in system
r'	Transmission rate
$R_0 = R_{Basic}$	Basic rate (Packets/time slot)
R_L	Receiver load resistor
R_{new}	New rate (Packets/time slot)
R_n	Nominal bit rate
R_s	Bit rate
$S = \{S_0, S_1, \dots, S_{\Phi-1}\}$	Set of FHC
SF	Spreading factor
T	Bit duration
T_c	Chip duration
T_n	Nominal bit duration
T_P	Packet time duration
T_s	Slot duration

T^o	Receiver noise temperature
u	Constant output of an optical hard-limiter
w	Code weight
x	Number of classes in system
Y_i	Number of photons collected from weighted chip i
Z	Total number of received pulses
Z_i	Number of received pulses per marked chip i
β	System throughput
β_1	Throughput Of class 1
β_2	Throughput Of class 2
$\beta_{overall}$	Overall system throughput
C	Cardinality of OCFHC/OOC
C_1	Available number of codes in class 1
C_2	Available number of codes in class 2
C_x	Available number of codes in class x
$\bar{\ell}$	Interference vector
\mathcal{R}	APD responsivity at unity gain
v'	Threshold level of the optical hard-limiter
λ_a	Autocorrelation constraint
λ_c	Cross-correlation constraint
θ	Decision threshold
φ	Maximum number of classes in system
Φ	Cardinality of OCFHC
$\Phi_{2-D_{ooc}}$	Upper bound of 2-D OOC's cardinality
Π_n	Stationary probability
$\Pi_{n_1}^1$	Stationary probability distribution of class 1
$\Pi_{n_2}^2$	Stationary probability distribution of class 2
$\Pi_{n_x}^x$	Stationary probability distribution of class x
μ	Average photons per bits
σ_{bi}^2	Conditional variance of the decision variable Y_i
σ_n^2	Variance of thermal noise within a chip interval

ABBREVIATIONS

BER	Bit Error Rate
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DS-CDMA	Direct Sequence Code Division Multiple Access
ECC	Error Correction Code
FHC	Frequency Hop Code
GMPLS	Generalized Multi Protocol Label Switching
LAN	Local Area Network
MAC	Media Access Control
MAI	Multiple Access Interference
MC	Multi-Coding
MCVW	Multi Code Variable Weight
MLVW-OOC	Multi Length Variable Weight Optical Orthogonal Code
MR/MS	Multi Rate Multi Service
OCDMA	Optical Code Division Multiple Access
OCFHC	One Coincidence Frequency Hop Code
OOK	On Off Keying
OPPM	Overlapping Pulse Position Modulator
OSI	Open Systems Interconnection
OVSF	Orthogonal Variable Spreading Factor
PD	Photo-Detector

Pro 1	Protocol 1
Pro 2	Protocol 2
QOS	Quality of Service
TDM	Time Division Multiplexing
TT/TR	Tunable Transmitter Tunable Receiver
VPG	Variable Processing Gain
VSL	Variable Spreading Length
WDM	Wavelength Division Multiplexing
WDMA	Wavelength Division Multiple Access
1D-OOC	One Dimension Optical Orthogonal Code
2-D OCFHC/OOC	Two Dimension One Coincidence Frequency Hop Code/Optical Orthogonal Code
2D-OOC	Two Dimension Optical Orthogonal Code

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