# 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

iv

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 |
| $C_{OOC} = \{a_1, a_2, \cdots, a_{|C|}\}$ | Set of direct sequance 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 |

| | |
|---|---|
| $N_{ooc}$ | OOC 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 |
| $S = \{S_0, S_1, \cdots, S_{\Phi-1}\}$ | 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-limitter |
| $w$ | 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 $i$ |
| $\beta$ | System throughput |
| $\beta_1$ | Throughput Of class 1 |
| $\beta_2$ | Throughput Of class 2 |
| $\beta_{overall}$ | Overall system throughput |
| $\mathcal{C}$ | Cardinality of OCFHC/OOC |
| $\mathcal{C}_1$ | Available number of codes in class 1 |
| $\mathcal{C}_2$ | Available number of codes in class 2 |
| $\mathcal{C}_x$ | 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 |
| $\lambda_a$ | Autocorrelation constraint |
| $\lambda_c$ | Cross-correlation constraint |
| $\theta$ | Decision threshold |
| $\varphi$ | Maximum number of classes in system |
| $\Phi$ | Cardinality of OCFHC |
| $\Phi_{2-D_{ooc}}$ | Upper bound of 2-D OOC's cardinality |
| $\Pi_n$ | 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 $x$ |
| $\mu$ | Average photons per bits |
| $\sigma_{bi}^2$ | Conditional variance of the decision variable $Y_i$ |
| $\sigma_n^2$ | Variance of thermal noise within a chip interval |

# ABBREVIATIONS

| | |
|---|---|
| **BER** | **B**it **E**rror **R**ate |
| **CDMA** | **C**ode **D**ivision **M**ultiple **A**ccess |
| **CSMA** | **C**arrier **S**ense **M**ultiple **A**ccess |
| **CSMA/CD** | **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection |
| **DS-CDMA** | **D**irect **S**equence **C**ode **D**ivision **M**ultiple **A**ccess |
| **ECC** | **E**rror **C**orrection **C**ode |
| **FHC** | **F**requency **H**op **C**ode |
| **GMPLS** | **G**eneralized **M**ulti **P**rotocol **L**abel **S**witching |
| **LAN** | **L**ocal **A**rea **N**etwork |
| **MAC** | **M**edia **A**ccess **C**ontrol |
| **MAI** | **M**ultiple **A**ccess **I**nterference |
| **MC** | **M**ulti-**C**oding |
| **MCVW** | **M**ulti **C**ode **V**ariable **W**eight |
| **MLVW-OOC** | **M**ulti **L**ength **V**ariable **W**eight **O**ptical **O**rthogonal **C**ode |
| **MR/MS** | **M**ulti **R**ate **M**ulti **S**ervice |
| **OCDMA** | **O**ptical **C**ode **D**ivision **M**ultiple **A**ccess |
| **OCFHC** | **O**ne **C**oincidence **F**requency **H**op **C**ode |
| **OOK** | **O**n **O**ff **K**eying |
| **OPPM** | **O**verlapping **P**ulse **P**osition **M**odulator |
| **OSI** | **O**pen **S**ystems **I**nterconnection |
| **OVSF** | **O**rthogonal **V**ariable **S**preading **F**actor |
| **PD** | **P**hoto-**D**etector |

| | |
|---|---|
| **Pro 1** | **P**rotocol 1 |
| **Pro 2** | **P**rotocol 2 |
| **QOS** | **Q**uality of **S**ervice |
| **TDM** | **T**ime **D**ivision **M**ultiplexing |
| **TT/TR** | **T**unable **T**ransmitter **T**unable **R**eceiver |
| **VPG** | **V**ariable **P**rocessing **G**ain |
| **VSL** | **V**ariable **S**preading **L**ength |
| **WDM** | **W**avelength **D**ivision **M**ultiplexing |
| **WDMA** | **W**avelength **D**ivision **M**ultiple **A**ccess |
| **1D-OOC** | **O**ne **D**imension **O**ptical **O**rthogonal **C**ode |
| **2-D OCFHC/OOC** | **T**wo **D**imension **O**ne **C**oincidence **F**requency **H**op **C**ode/**O**ptical **O**rthogonal **C**ode |
| **2D-OOC** | **T**wo **D**imension **O**ptical **O**rthogonal **C**ode |

# List of Tables

# List of Figures