State Estimation in Optical CDMA Networks

Purushotham Kamath, Joseph D. Touch, Joseph A. Bannister
USC/ISI
4676 Admiralty Way
Marina del Rey, CA 90292
{pkamath, touch, joseph}@isi.edu

***Abstract*— State estimation is a mechanism to estimate the state of an optical CDMA network. It can prevent degradation of throughput at high offered load when used as part of *Interference Avoidance*, a contention media access control protocol for optical CDMA Local Area Networks. Optical CDMA is a multiple access technique for broadcast optical LANs. The throughput of an optical CDMA LAN at high offered load is limited by multi-user interference. Interference Avoidance, prevents throughput degradation at high loads. It consists of *state estimation* and *transmission scheduling*. This work proposes algorithms for state estimation and studies the performance of Interference Avoidance under these algorithms. The analysis shows that the performance is sensitive to the state estimation algorithm and its parameters. When used with codesets of long lengths (> 100) and low weight (< 5), state estimation prevents throughput collapse and stabilize throughput at around 30% of the maximum. The throughput of Interference Avoidance with the state estimation algorithms is within 20% of throughput with optimal state estimation.**

KEYWORDS: System design, Optical CDMA

I. Introduction

This work considers a shared medium, packet switched optical CDMA LAN in which several nodes are connected to a passive star coupler to form an all optical broadcast network. Each node on the network is allocated an optical CDMA codeword to receive on. Optical CDMA codewords are sequences of zeroes and ones (unipolar codewords) that are transmitted asynchronously. The codewords are transmitted by binary intensity modulation *i.e.* a one in the codeword is represented by pulse of light. Nodes use ON-OFF keying of the codeword to transmit binary data. To transmit a 1 bit the codeword is sent and to transmit a 0 bit, an all zeros codeword is sent. When a node wants to transmit, it tunes its transmitter to the receiver's codeword and transmits. The code division multiplexing allows several pairs of users to communicate simultaneously.

The throughput of an optical CDMA LAN is limited by multi-user interference. When several users transmit simultaneously, their packets and hence their codewords overlap. When the optical pulses in the codeword overlap, their optical power is added. Optical pulses from one codeword can be detected by receivers tuned to other codewords. As a result receivers may falsely detect their codewords resulting in packet errors. These false positive errors increase with offered load, resulting in throughput collapse.

Interference Avoidance is a contention media access control mechanism that prevents throughput collapse in optical LANs networks at high offered load. It consists of *state estimation* and *transmission scheduling*. State estimation is a mechanism by which nodes on the network estimate the state of the line. Transmission scheduling is a mechanism by which nodes use the estimated state to schedule their transmissions to avoid packet losses due to interference.

The contribution of this paper is the analysis of state estimation algorithms for optical CDMA networks. The analysis shows that when state estimation parameters (number of estimation samples) and the codeset parameters (length and weight) are chosen appropriately, the algorithms perform with 20% of optimal state estimation. Evaluation of the algorithms with different traffic models indicates that they prevent throughput degradation with real network traffic.

The paper is organized as follows. Section II provides background on optical CDMA. Section III discusses the motivation for Interference Avoidance. Section IV defines state in optical CDMA networks and discusses its properties. Section V defines the state estimation algorithms. Section VI analyzes the performance of the transmission scheduling algorithms under different algorithm and codeset parameters. Section VII discusses the related work in this field. Section VIII discusses conclusions and future work.

II. Background

This section provides background on optical CDMA LAN architecture, codeset design and receiver design.

A. Optical CDMA LAN architecture

The optical CDMA network considered in this work is a *shared medium, packet switched, multiple access* LAN. The physical layer is optical CDMA that uses unipolar encoding and intensity modulation over a single wavelength.

The network consists of several nodes connected by optical fiber to a passive star coupler as shown in Figure 1. The optical coupler consists of several inputs and output ports. Each node is connected to one input and one output port by a transmit and receiver fiber respectively. Signals transmitted on the inputs enter the coupler, merge and are transmitted on all outputs. The star coupler is passive *i.e.* the input power is split equally

[1]This material is based upon work supported by the Defense Advanced Research Projects Agency under contract no. N66001-02-1-8939 issued by the Space and Naval Warfare Systems Center (SPAWAR). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Defense Advanced Research Projects Agency, SPAWAR, or the U.S. Government.

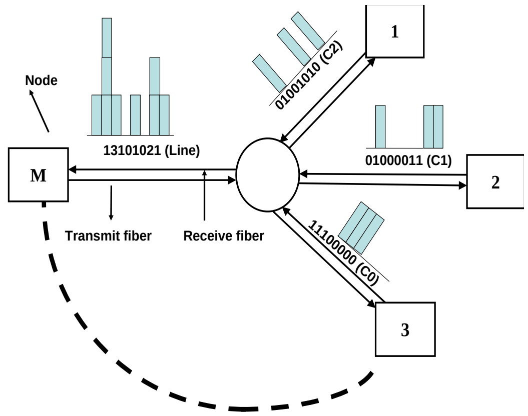

Fig. 1. Typical optical CDMA LAN topology. Nodes are connected by transmit and receive fibers to a passive optical coupler in a star topology.

among the receive fibers and is transmitted to all nodes on the receive fibers. The signal at the output of the coupler on any receive fiber is given by

$$r(t) = (1/K)\sum_{i=1}^{K} s_i(t)$$

where K is the number of ports connected to the coupler and $s_i(t)$ is the signal entering on the i^{th} transmit fiber. The signals on the transmit fibers $s_i(t)$ are binary optical signals and the signal on a receive fiber $r(t)$ is a multilevel optical signal. The signal on the receive fiber may be amplified or attenuated after the coupler.

The network is based on a *Tunable Transmitter-Fixed Receiver (TT-FR)* architecture. A receiver chooses a codeword to receive on and a transmitter which needs to communicate with a receiver tunes to the receiver's codeword. A TT-FR architecture eliminates the need for pre-transmission coordination [1]. The network uses *codeword sharing*. If the number of nodes is greater than the codewords, the codewords are shared among receivers. A higher layer unique identifier such as a link layer address is used to demultiplex packets sharing a codeword. Every node runs a *frame synchronization algorithm* [2] which allows the node to identify that a frame destined for it has arrived and where the first bit of the frame begins.

B. Optical CDMA codeset design

An Optical Orthogonal Codeset (OOC) is a set of (0,1) sequences of length N that satisfies correlation constraints [3]. The term *codeset* is used to refer to the set of sequences, and the term *codeword* is used for a member of the set. Each 0 or 1 of a sequence is called a *chip*, and the codeword represents a data *bit*. For any two codewords in the codeset, the correlation constraints are:

$$\sum_{n=0}^{N-1} s_{(i,n+\tau)} s_{(j,n)} \quad \begin{array}{ll} = w & \text{when} \quad i = j, \tau = 0 \\ \leq \kappa & \text{otherwise} \end{array}$$

where $s_{(i,n)}$ is the n^{th} chip of the i^{th} codeword, addition is modulo N and $0 \leq \tau \leq N-1$. κ is called the *Maximum Collision Parameter*. The number w of '1 chips' of a codeword of the codeset is called its weight. A particular codeset is specified by the parameters (N, w, κ). The size S of the codeset is the number of codewords in the codeset. Codesets with all codewords having the same weight are called *constant weight* codesets. [3] and [4] describe several codeset construction methods. The codesets used in this work are constant weight codesets generated by the greedy construction method [3]. The rate at which individual chips are transmitted is called the *chipping rate* B. The rate at which the data bits are transmitted is called the *data rate*. The chipping rate is N times the data rate. The codewords are *pseudo-orthogonal* because optical CDMA uses unipolar encoding[1].

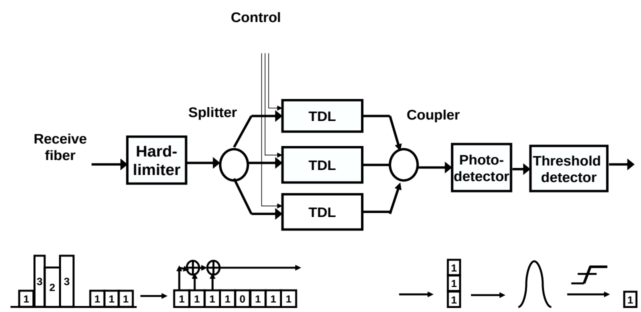

Fig. 2. Optical CDMA receiver: The figure shows a hard-limiting correlation detector that consists of a hard-limiter, decoder, photo-detector and a threshold detector. The receiver is tuned to the codeword 1110000. The power in the 1^{st}, 2^{nd} and 3^{rd} chip positions is summed by the decoder. The photo-detector converts the signal to an electrical signal and the threshold detector detects a 1 bit.

C. Optical CDMA receiver design

The optical CDMA receiver (also called a decoder) is a hard-limiting *correlation* receiver [5]. The receiver decodes the codeword in the received signal and regenerates the transmitted data. Figure 2 depicts the operation of a receiver. The input signal from the coupler is a multilevel optical signal. The receiver converts it to a digital optical signal by hard limiting the power in each chip of the received signal. It then decodes the signal to detect a 1 or 0 bit. Let R be the received signal (an N dimensional vector whose components are non-negative integers), and C the codeword being received (an N dimensional vector whose components are binary values). Let $R = [r_0 r_1 r_2 ... r_{N-1}]$ and $C = [c_0 c_1 c_2 ... c_{N-1}]$. Then the received bit b is given by

$$\begin{aligned} b \quad &= 1 \quad \text{if} \quad (C \cdot h(R) \geq w) \\ &= 0 \quad \text{otherwise} \end{aligned}$$

[1]This contrasts with CDMA on the wireless medium where bipolar encoding is feasible. Bipolar codewords can be designed to be orthogonal.

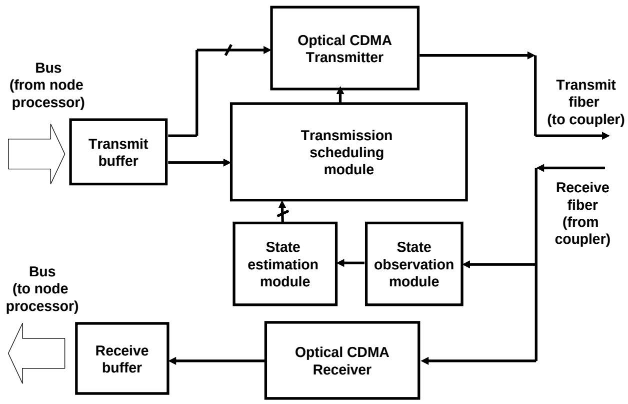

Fig. 3. Block diagram of an Interference Avoidance Network Interface Card.

where the dot product $\cdot$ of two vectors $[u_0u_1...u_{N-1}] \cdot [v_0v_1...v_{N-1}] = \sum_{i=0}^{N-1} u_iv_i$ and $h()$ is the hardlimiting operation defined as

$$\begin{aligned} h(R) = \quad & [s_0s_1...s_i...s_{N-1}] \\ \text{where} \qquad & s_i = 0 \qquad \text{if} \quad 0 \le r_i < 1 \\ & s_i = 1 \qquad \text{if} \quad r_i \ge 1 \end{aligned}$$

III. Interference Avoidance

Interference occurs due to the multiplexing of packets on a receive fiber. Interference errors increase as the offered load on the network increases. [6] discusses the need for Interference Avoidance and shows that without media access control, at high offered load (100%) the throughput of the network approaches zero.

Interference Avoidance is a contention media access control (MAC) protocol. Each node on the network contends for access to the medium using the Interference Avoidance protocol. Figure 3 shows a block digram of an Interference Avoidance Network Interface Card. It consists of an optical CDMA transmitter, optical CDMA receiver, state estimation module and transmission scheduling module.

Transmission scheduling is a process by which a node, given a state estimate and a codeword to be used for encoding, calculates a codeword delay (a value k where $0 \le k < N$) such that interference errors are reduced (the state of the line is a function of the signal on the receive fiber and will be defined formally in Section IV). Transmission scheduling is invoked on arrival of a packet from the node processor and is done on a per packet basis. If transmission is not possible, then the packet transmission is deferred by returning it to a higher layer for a retransmission attempt. The optical CDMA transmitter encodes the data and begins transmission after the delay. The transmission scheduling module is purely electronic and must compute the transmission delay within a few bit times of the current packet's arrival. The electronic part of the state estimation module and the transmission scheduling module may be integrated and implemented in a single ASIC chip and optimized for minimum latency.

Several transmission scheduling algorithms were discussed in [6] under the assumption of perfect state estimation. Three algorithms were evaluated: Pure selfish scheduling, Overlap section scheduling and Threshold scheduling. Pure selfish scheduling schedules transmissions such that at least one of its 1 chips does not overlap with chips in the estimated state. Overlap Section scheduling schedules transmissions such that at least one of its 1 chips does not overlap and the number of overlaps in the resulting state is below the number of ones. The threshold scheduling algorithm schedules packet transmissions such that at least one of its 1 chips does not overlap and the number of chip overlaps in the resulting state is below a threshold. The threshold is expressed as a fraction of the codeword length N, called the *threshold parameter* α. Analysis and simulation showed that all the algorithms prevented throughput collapse when used with appropriate codeset parameters.

State estimation is a process by which a node calculates an estimate of the state from a series of observations of the signal on the receive fiber. The state estimate is used as input to the transmission scheduling algorithm. The state estimation module performs two functions: collect state observations and state estimation. It receives the multilevel optical signal on the receive fiber and collects observations of the state of the line. It uses a series of state observations to calculate a state estimate. The state estimation algorithm is always active. It is run continuously in a loop, collecting state observations and calculating a state estimate. The state estimation module consists of both optical and electronic components. This paper examines the state estimation problem. Section IV will define the state and Section V will formally state the state estimation problem and algorithms, Section VI will discuss the performance of state estimation when used with the three transmission scheduling algorithms.

IV. State of the Line

The following section defines the state of an optical CDMA LAN. It describes *coherence*, a property of the state that makes state estimation feasible.

A. State of the line

The state of the line (also called state of the network) at a point in time and space on a shared medium is a variable that can be used to predict the result of transmitting a packet at that point at that time[1]. The *state* of the line for an optical CDMA LAN at a time and a point on the line is a vector of length N equal to the sum of the codewords at that point and time assuming that all nodes are transmitting 1 bits.

$$S(d,t) = [s_0s_1s_2....s_{N-1}] = \sum_{i=0}^{M} rot(C_i, \phi_i)$$

[1]The prediction assumes that the state does not change during the transmission of the packet. In the case of an optical CDMA LAN the state is a variable that can be used to predict the result of transmitting a codeword at that point at that time.

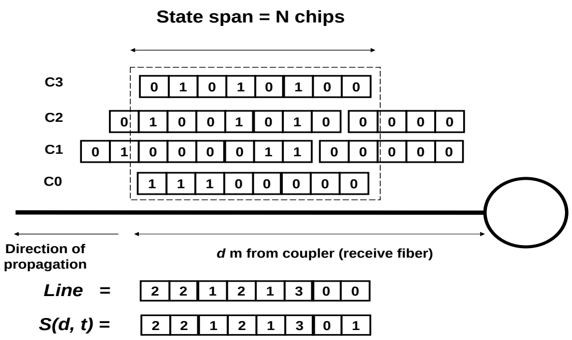

Fig. 4. The figure shows the state of the line at a point on a receiver fiber. The state of the line at time t at distance d is [2 2 1 2 2 3 0 1]. The second bit of codeword *C1* is OFF. To calculate the state, *C0* is assumed to be ON and the codewords are added.

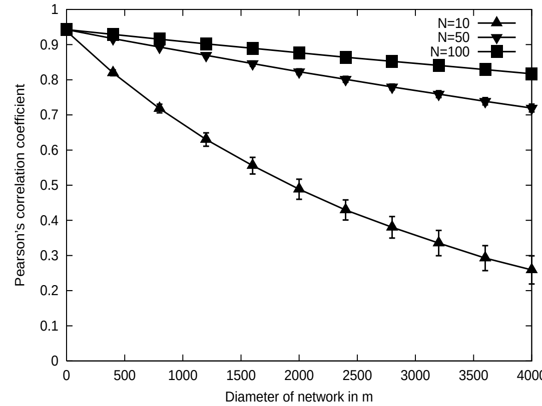

Fig. 5. The graph shows the correlation between the state at the estimation point at estimation time and the merging point at merging time for an optical CDMA network as the diameter of the network is increased. The network has 100 nodes distributed uniformly over the length of the network. The network uses Aloha-CDMA. Packet arrivals are Poisson with offered load 1 and packet lengths are exponentially distributed with an average length of 1000 bytes.

where M is the number of codewords on the line at the output of the coupler at time t, $C_i = [c_0 c_1 ... c_{N-1}]$ is a codeword present at the output of the coupler, $rot(C_i, \phi_i)$ is a vector of length N equal to the left rotation of the codeword C_i by ϕ_i and ϕ_i is the number of chips between C_i's leading chip (*i.e.* the chip that was transmitted first, c_0) and the point of measurement. The state is the sum of codewords each shifted by different codeword delays due to the different packet arrival times. It is a hypothetical, idealized representation of the state of the system. It is possible that the state may never actually be observed as a signal on the optical fiber. In Figure 4, the second bit of codeword *C1* is OFF. To calculate the state, assume that it is ON and add the codewords. The state in Figure 4 is $S(d, t)$ = [2 2 1 2 1 3 0 1].

A *state observation* is a vector of length N equal to the signal observed by a node on its received fiber. The signal on the receive fiber is a multilevel optical signal. In Figure 4, a node would observe the signal [2 2 1 2 1 3 0 0]. The state observations at the same distance from the coupler on different receive fibers is the same because all receive fibers carry the same signal. This is a consequence of the low noise, guided medium characteristic of the physical medium.

The state consists of N chips. It follows that state at a point is measured over a time interval of Nt_c where t_c is the time to transmit a chip. In spatial terms, it is measured over a distance Nt_d where t_d is the length of a chip on the fiber. Therefore, to avoid overlap in the state measurement, successive state observations at a point should be collected at intervals of Nt_c (or integral multiples of Nt_c). Similarly, state at an instant should measured at points that are separated by distance of Nt_d (or integral multiples of Nt_d). The times when state is measured at a point are called the *state measurement instants*. The points where state is measured are called the *state measurement points*. State measured at these points and instants may be compared. A *state transition* is defined as the change of state at a point on the line from one state measurement instant to the next. A state transition occurs due to a packet arrival or departure. Note that state observations at a point may change between state measurement instants due to ON/OFF keying of codewords. However the state does not change due to ON/OFF keying, only due to packet arrivals or departures.

B. Coherence of state

Coherence of state is a property by which state at a state measurement point and instant is correlated to the state at some other state measurement point and instant. States measured at two point and at two instants may differ due to state transitions between the measurements.

The correlation between two states can be measured using the Pearson correlation coefficient [7]. The Pearson's correlation coefficient between two vector samples X and Y is defined below:

$$r = \frac{\sum_{i=1}^{N}(x_i - \overline{X})(y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{N}(x_i - \overline{X})^2 \sum_{i=1}^{N}(y_i - \overline{Y})^2}}$$

where x_i are the elements of a vector X, and $\overline{X}$ is the mean of the elements. It is a number between -1 and 1 and indicates the extent of a linear relationship between two measured quantities. A value of 0.8 and above generally indicates a strong degree of linear correlation.

A simple experiment shows that an optical CDMA network exhibits the property of coherence. Consider an Aloha-CDMA optical CDMA network *i.e.* an optical CDMA network without any media access control. Packet arrivals are Poisson and the offered load is 1. The packet size is exponentially distributed with average size 1000 bytes. The chipping rate is 10 *Gc/s*. The offered load is 1. The number of nodes on the network is 100 and the nodes are at uniformly distributed distances from the coupler. Figure 5 shows the average correlation between the state at a node (estimation point/time) and the state at the output of the coupler (merging point/time)(merging point/time) as the diameter of the network is increased. The graphs

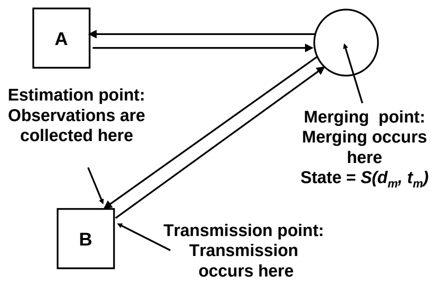

Fig. 6. The figure shows the points where state estimation and transmission merging take place. The state is estimated by a node at its estimation point at the estimation time. The node transmits a packet at the transmission time and it merges with other packets at the merging point (coupler) at the merging time.

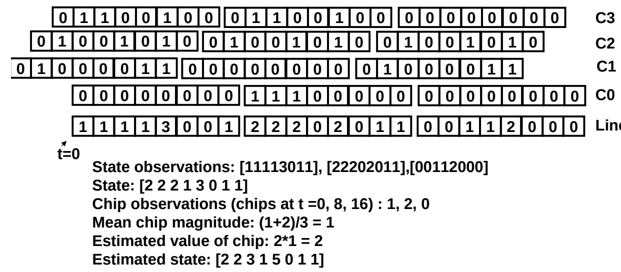

Fig. 7. The figure shows observations of the state at a point. The state estimation algorithm calculates a state estimate from the state observations.

are plotted for different codeset lengths. The graph shows that as the diameter of the network increases, the correlation between the state at the node and the coupler decreases. As the codeset length increases the correlation increases. There are two reasons why the coherence increases as N increases:

- Packet elongation: As N increases, the physical length of the packet on the line increases. For two points a fixed distance apart, as N increases, the correlation between state at the two points increases.
- Reduced probability of chip change: For two points a fixed distance apart, as N increases, the probability that a change occurs in any particular chip of the states at the two points due to a new arrival/departure reduces. This results in increased coherence.

For diameters of upto 4000m, a codeset length of $N = 100$, shows a reasonable amount of correlation. This indicates that under certain conditions the state of the optical CDMA network exhibits coherence. The coherence can be exploited. If state can be estimated accurately at the estimation point, then it can be used as an estimate of state at the merging point and merging time.

V. State estimation

State estimation is the process by which a node calculates an estimate of the state at a point on the line at a time using state observations obtained at some (possibly different) point on the line at some (possibly different) time. The estimated state is used as input to a transmission scheduling algorithm.

A. The state estimation problem

The state estimation problem can be stated as follows: Given a series of observations of the state $S_0, S_1, S_2, ...S_{K-1}$ at times $t, t+t_b, t+2t_b, ...t+(K-1)t_b$, (where t_b is a bit time) calculate an estimate of the state such that the throughput of the transmission scheduling algorithm is maximized.

Figure 6 illustrates the process of state estimation. Node B is the node estimating the state. It collects K observations of the state from the signal at the estimation point. The state estimation algorithm takes the K observations of the state as input. It calculates an estimate of the state called the *estimated state*. It uses this value as the input to the transmission scheduling[1].

B. Distribution of the state

It is necessary to determine the distribution of the state, in order to determine the most suitable state estimation algorithm. This section shows that the probability distribution of the chip magnitude of the components of the state observation is a binomial distribution. Therefore the sample means estimator is the optimal estimator for the state.

Consider K state observations collected at a point on the receive fiber. Assume that no state transitions *i.e.* packet arrivals or departures occur during the collection of state observations and that the probability of a 1 data bit being transmitted is $p = 0.5$. The state at the point at every state measurement instant is the same, say S. The only reason that the state observations are different is the ON-OFF keying of the codewords. Consider the K observations of the first chip of each state observation. These *chip observations* form a time series of K observations. Consider the first chip of the corresponding state S. Assume that first chip of the state S has chip magnitude m. The chip observation is the sum of the m chips where each chip is turned ON or OFF with probability $p = 0.5$[2]. Therefore the chip observations may

[1]This work assumes that the estimation point and transmission point are separated by a distance which is an integral multiple of Nt_d. If this is not true, a ranging procedure will be needed to determine the difference and rotate the estimated state by the appropriate offset.

[2]This argument assumes that 0 or 1 data bits are transmitted with equal probability (*i.e.* 0.5). If the probability is different (say, due to the use of a higher layer encoding such as 4B/5B), then the value of p must be changed accordingly. The higher layer encoding may be chosen to ensure a particular value of p.

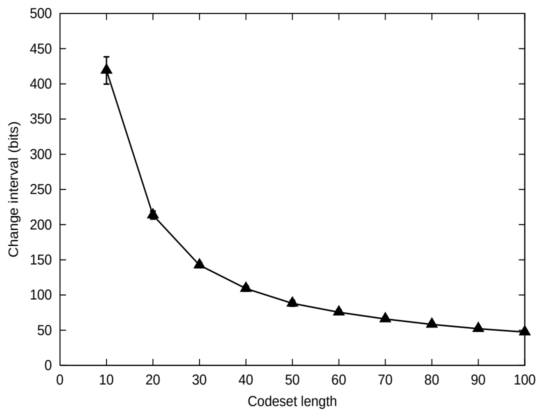

Fig. 8. The figure shows the mean number of bit transmission times between a state transition for different codeset lengths at an offered load of 1. The network is an Aloha-CDMA network with Poisson arrivals and exponentially distributed packet lengths. The average packet length is 1000 bytes.

be considered to be the number of successes in a series of m Bernoulli trials. Therefore the distribution of the chip magnitude of the chip observations is a Binomial distribution. The mean number of successes of a binomial distribution of m trials where p is probability of success is $\mu = mp$. The mean of a stationary binomial distribution can be estimated by using a *sample means* estimator [7]. It can be shown that for the binomial distribution the *sample means estimator* is the estimator for the mean that minimizes the estimation error. It is a minimum variance, unbiased maximum likelihood estimator which can be shown to converge to the mean as the number of observations increases. If the sample mean is μ_e, then $\mu_e = mp$, where $p = 0.5$, *i.e.* $m = 2\mu_e$. The procedure can be applied to the observations of each element and the estimated state vector can be calculated.

E.g. Figure 7 shows three state observations [11113001], [22202011] and [00112000]. The chip observations from the first chip of each of the state observations are 1, 2, 0. In Figure 7, the state is [22213011]. The true value of the element in the first chip is 2. So in Figure 7, 1, 2, 0 are observations of the number of successes in a Bernoulli trials with $m = 2$. The mean value is $(1+2+0)/3 = 1$. Therefore the estimated value is $2*1 = 2$. The same can be repeated for every element of the state vector. The estimated state vector in Figure 7 is [22315011].

The sample means estimator is the optimal estimator provided that the distribution is stationary *i.e.* the state does not transition during the collection of observations. A state transition (an arrival or a departure of a packet) may change the mean of the distribution of the chip observations of the state observations. If the time needed to collect sufficient number of observations of the state is comparable to the interval between state transitions then the estimation error increases because the distribution is no longer stationary [1]. However, to to justify the sample means estimator, it must be shown that the interval between state transitions is larger than the time needed to collect sufficient observations.

The sample means estimator may be justified by a simple experiment that determines the interval between state transitions. Consider a optical CDMA LAN using Aloha CDMA with Poisson arrivals and exponentially distributed packet lengths. The average packet length is 1000 bytes. The normalized offered load is 1. Figure 8 shows the average interval (in bit transmission times) between changes of the state of the line at a point. The interval between state transitions is shown for different codeset lengths. Note that the graph shows the interval between state transitions in terms of bit times. This is intentional: the time to collect a single observation of the state depends on the codeset length. In one bit time, 1 observation of the state can be collected. Therefore the time between state transitions in bit times gives a measure of how slow the state is changing in comparison to the observation collection time. Even for codeset lengths of 100, state transitions happen on an average every 50 bits. For transmission scheduling algorithms which allow less packets on the line at 100% offered load, the interval between state transtions will be larger. Section VI will show that a sample means estimator needs around 10-20 observations to obtain a reasonable estimate of the state. Therefore there are very few state transitions during the collection of observations. Under these conditions the sample means is a reasonable estimator[2].

C. Parameters

The state estimation hardware consists of a *observation module* and an *estimation module*. The observation module collects observations and the estimation module uses the observations to estimate the state. This section describes the observation and estimation parameters.

1) Observation parameters: The three parameters that control observations are

- Observation start time t_s: The time when the observation starts.
- Observation count n_s: The number of state observations collected.
- Buffer size b_s: The number of state observations that can be stored. The buffer is assumed to be a FIFO queue.

For example, if $t_s = 0$ and $n_s = \infty$, sampling begins when the node is switched on and the node collects observations continuously. If $t_s = t_a$ and $n_s = 5$, sampling begins when

[1] A non stationary distribution where the mean changes at a rate comparable to the rate at which observations are collected or which has a high variance is best estimated using a smoothed average rather than a sample means. For example, the Round Trip Time (RTT) estimator for the Transmission Control Protocol (TCP) uses an exponentially smoothed estimator because the rate at the which the RTT varies is comparable to the rate at which observations are collected.

[2] Note that these conditions may change depending on the traffic model. A different traffic model may change the interval between state changes and may require a different estimator. Section VI studies the performance of state estimation under realistic traffic and finds that the performance does not degrade noticeably.

```
estimate()
{
  p ← 0.5
  eststate ← 0
  totalstate ← 0
  for count = 1 to n_e
    totalstate+ =buffer[count]
  eststate ← totalstate ∗ /(pn_e)
}
```

TABLE I

THE *Sample means* STATE ESTIMATION ALGORITHM.

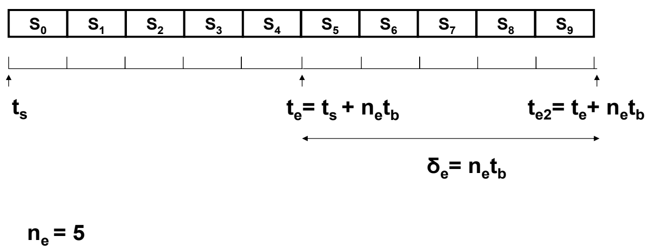

Fig. 9. The figure shows the state estimation parameters. It shows 10 state observations. The collection of state observations begins at t_s. Estimation is run after $n_e = 5$ observations are collected at time t_e.

a packet arrives and ends when 5 observations have been collected. State observations are stored in a circular buffer of size b_s state observations. When the buffer is full, the oldest values are overwritten.

2) Estimation parameters: The three parameters that control sampling are

- Estimation start time t_e: The time when the estimation algorithm is started.
- Estimation count n_e: The number of state observations used by the estimation algorithm.
- Inter-estimation time δ_e: The time between successive runs of the state estimation algorithm.

Estimation can be started at any time when there are at least n_e state observations available. The estimation algorithm takes as input the observations in the buffer (at least n_s observations). Its follows that the following relationship must hold: $b_s \geq n_s \geq n_e$. The estimation algorithm is shown in Table I. The computation complexity of the estimation algorithm is O(n_e). Therefore, the latency of the estimation algorithm is controlled by n_e.

D. State estimation algorithms

The sampling and estimation parameters control when the state estimate becomes available for use by the transmission scheduling algorithm. Transmission scheduling begins after a packet arrives and the state estimate is available

The parameters control a trade off between the access latency and the state estimation accuracy. The access latency can be minimized if, on packet arrival, transmission scheduling is started immediately using the last calculated state estimate. However this may result in a less accurate state estimate because of possible state transitions in the time between the last state estimation and transmission scheduling.

The estimation accuracy can be maximized by using the state estimate as soon as it is available. A way to do this is to defer transmission scheduling until a new state estimate is available. However this results in an increase in access latency.

To evaluate this trade off this work will consider two algorithms:

- Continuous estimation: $t_s = 0; n_s = \infty; t_e > n_e t_b, t_e < t_{arr}; \delta_e = t_b; n_e = 10$ to 100: The collection of observations begins when the node starts up and are collected every bit time. Estimation is begun anytime before the first packet arrives. It is repeated after n_e new observations are collected (it is assumed that the state estimation hardware can be designed to complete before n_e observations are collected). When a packet arrives for transmission, transmission scheduling uses the last estimated state. Continuous estimation minimizes access latency but uses a potentially less accurate state estimate.
- On demand estimation: $t_s = t_{arr}; n_s = n_e; t_e = t_a + n_e t_b; \delta_e = \delta_a; n_e = 10$ to 100: Observations are collected on packet arrival and n_e observations are collected. Estimation is done after observations are collected. When a packet arrives for transmission, observations are collect, state is estimated and transmission scheduling uses the latest estimated state. On demand estimation uses the most accurate state estimate but suffers maximum access latency.

Other values of the sampling and estimation parameters are possible. Section VI will show that the parameters of the state estimation algorithm do not significantly impact the performance as long as n_e is sufficiently large and t_e is within a few bit times of the start of the transmission scheduling. This is because the coherence of the system is high (high correlation of state over distances of around 1000m), and the state remains constant for periods in the order of 100s of bit transmission times Therefore a using a state estimate that is 10s of bit transmission times old does not result in noticeable degradation.

VI. PERFORMANCE STUDY

When state estimation is used with transmission scheduling there are three sources of interference. The three causes are listed below. It is important to note that they increase interference *i.e.* chip overlaps. However the condition for a bit error is w chip overlaps. The w chip overlaps may be due to any combination of the causes. Therefore while interference may be attributed to the causes, a particular packet loss cannot be attributed to any one particular cause.

Parameter	Default value
Codeset parameters:	
Codeset length N	100
Number of wavelengths A	1
Codeset weight w	3
Maximum cross-correlation parameter κ	3
Number of codewords in codeset	100
Chipping rate:	10Gb/s
Codeword allocation:	Uniform random
Interference Avoidance parameters:	
Transmission scheduling algorithm:	Threshold scheduling
Threshold:	0.3
State estimation algorithm:	Continuous state estimation
Window:	10 $bits$
Traffic parameters:	
Inter-arrival time distribution	Exponential
Normalized offered load	1
Packet size distribution	Exponential
Average packet size	1000 $bytes$
Destination address distribution:	Uniform random
Topology parameters:	
Node to coupler distance distribution	Uniform
Average node to coupler distance	1000 m
Number of nodes	100

TABLE II

PARAMETER LIST AND DEFAULT VALUES FOR THE STATE ESTIMATION PERFORMANCE STUDY.

- Erroneous transmission scheduling: When a transmission scheduling algorithm is used, a small fraction of the packets are lost due to interference. This is because the algorithm does not guarantee that all transmissions will be scheduled without error [6].
- Collisions: A *collision* is an event where two or more nodes schedule their transmissions using state estimates that do not contain each others' codewords. Collisions are caused due to a state transitions between the state estimation and merging of the transmitted packets.
- Erroneous state estimation: An error in state estimation can occur for two reasons:
  - State transitions: A state transition may occur during the collection of observations.
  - Low number of state onbservations: If the sample size is not large enough, the sample mean will not approach the distribution mean.

A. Performance of state estimation

Figures 10, 11 and 12 show the throughput curves for continuous state estimation with nodes located at different distances from the coupler (uniformly distributed with an average distance of 1000m). The performance under perfect state estimation in a network with normalized propagation delay $a = 0$ was studied in [6]. Perfect state estimation is defined as state estimation where every node knows the state of the line at the output of couplers and all nodes see the same state at the same time. Under these conditions, the only cause of error is erroneous transmission scheduling. The throughput for threshold scheduling with perfect state

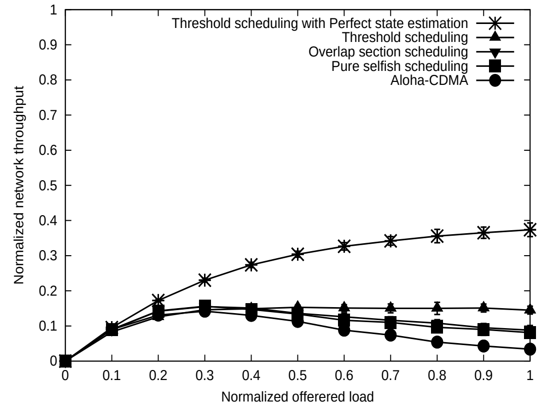

Fig. 10. The graph shows normalized network throughput vs. normalized offered load for continuous state estimation, normalized propagation delay $a > 0$ (average distance from the coupler is 1000m). The results are based on simulation. The codeset length is 10. All other parameters are as specified in Table II

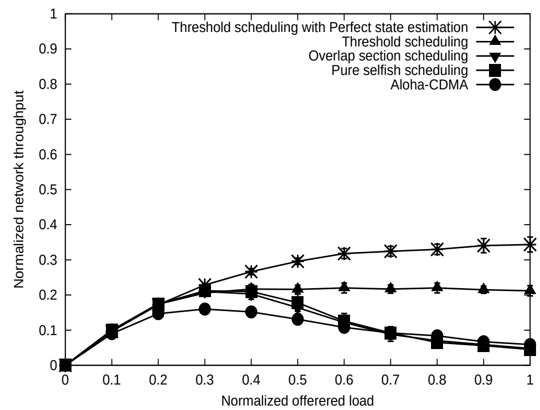

Fig. 11. The graph shows normalized network throughput vs. normalized offered load for continuous state estimation, normalized propagation delay $a > 0$ (average distance from the coupler is 1000m). The results are based on simulation. The codeset length is 100. All other parameters are as specified in Table II

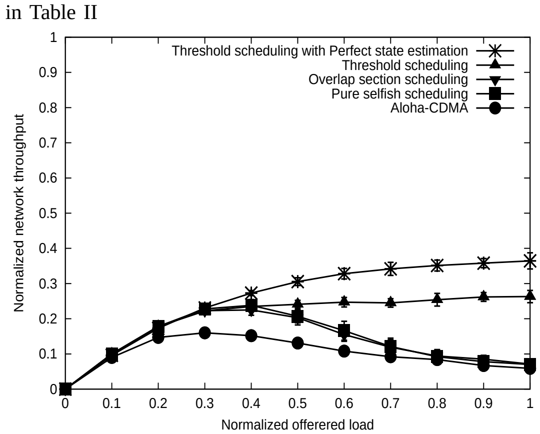

Fig. 12. The graph shows normalized network throughput vs. normalized offered load for continuous state estimation, normalized propagation delay $a > 0$ (average distance from the coupler is 1000m). The results are based on simulation. The codeset length is 200. All other parameters are as specified in Table II

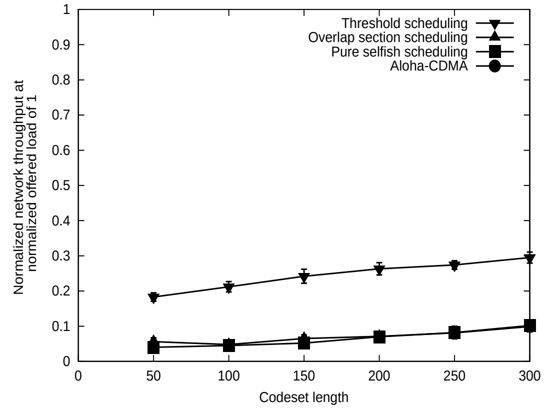

Fig. 13. The graph shows normalized network throughput vs. codeset length N for different transmission scheduling algorithms and on-demand state estimation. The results are based on simulation. The traffic model is Poisson arrivals with exponentially distributed packet lengths. The codeset is $(N, 3, 3)$ and codewords are chosen uniform randomly. For the threshold scheduling algorithm, the threshold parameter was set to 0.3. All other parameters are specified in Table II

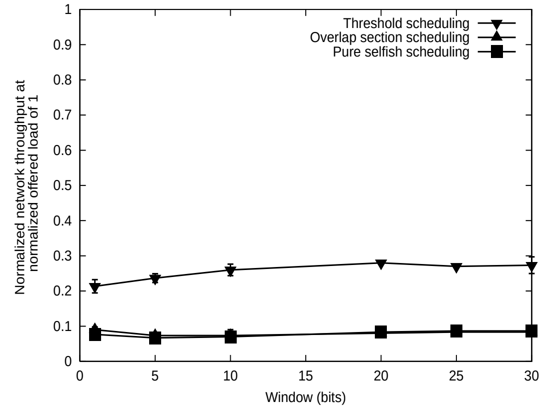

Fig. 14. The graph shows normalized network throughput vs. number of observations (bits) for the transmission scheduling algorithms and on-demand state estimation. The results are based on simulation. All other parameters are specified in Table II

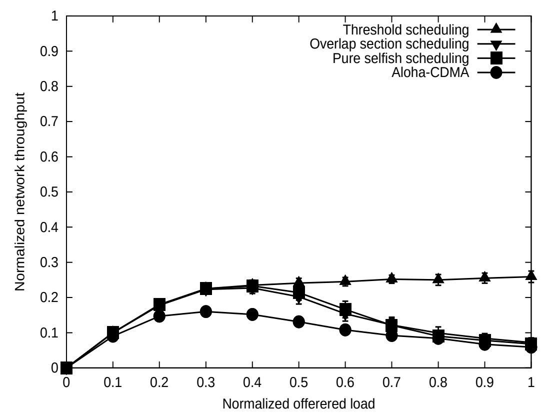

Fig. 15. The graph shows normalized network throughput vs. normalized offered load for on demand state estimation, normalized propagation delay $a > 0$ (average distance from the coupler is 1000m). The codeset length is $N = 200$. The results are based on simulation. All other parameters are specified in Table II

estimation in shown in the graphs. The throughput at high offered load of the continuous state estimation algorithm with the three transmission scheduling algorithms is lower than that of perfect state estimation. The reason for this are the two new sources of errors: collisions and erroneous state estimation. This results in the decrease in throughput. To compensate for this nodes must transmit conservatively. In particular, threshold transmission scheduling with a low threshold value (0.3) is suitable. This is indicated by the throughput collapse of both selfish and overlap section scheduling.

Despite conservative transmission the throughput of threshold scheduling decreases significantly for codeset length $N = 10$. However this effect reduces as N increases to 100 and 200. Figure 13 shows the effect of varying the codeset length N. [6] showed that with perfect state estimation and normalized propagation delay $a = 0$, the codeset length had no effect on transmission scheduling. In contrast, Figure 13 shows that increasing N improves the throughput. Section IV discussed the property of coherence. It showed that as N increases the correlation between the state at the estimation point and the state at the merging point increases. One of the causes for errors in state estimation is collisions. Collisions are due to state transitions between the time of state estimation and the merging time of packets. The number of collisions that occurs is independent of N because it depends only on the number of arriving packets *i.e.* the offered load. However the number of interference errors caused by collisions reduces as N increases because it is less likely that the colliding packets will interference with each other. This is the reason for the increased coherence as N increases. The result is that the throughput increases as N increases.

B. Effect of varying the number of state observations

Figure 14 shows the effect of varying the number of state observations on the throughput. Increasing it beyond 10 bits, it does not have an appreciable difference in improving the throughput. Though the increase will produce a more accurate state estimate, the increased accuracy does not translate into corresponding throughput gains. This is because threshold scheduling algorithm can function with a less than accurate state estimate. Threshold scheduling requires information about the position of 0s, 1s and overlaps in the state. It does not need the magnitudes of the overlaps. Therefore a small number of observations produces all the benefit that transmission scheduling can provide.

C. Effect of different estimation algorithms

Figure 15 shows the throughput curves for on-demand state estimation for $N = 200$. Comparing with Figure 12 indicates that there is no difference between the performance of on-demand and continuous state estimation. This is because small number of observations (10) provide enough information for transmission scheduling. The probability of a state transition during the collection of observations is low. As a result the state estimated by on demand and continuous state estimation is very close. Therefore, continuous state estimation performs the same as on demand state estimation. Given that continuous state estimation has minimum access latency, it is the preferred choice for a state estimation algorithm.

D. Effect of varying the average distance from the coupler

Figures 16, 17, 18 show the effect of increasing distance on the throughput The effect of increasing the diameter of the network is to increase the probability of collisions. As before this effect can be mitigated by increasing the codeset length N.

E. Performance with real network traffic

Figure 19 shows the performance with realistic network traffic. The network traffic was based on a traffic trace from an OC48 link. To generate the required load several traces were merged. The packet sizes, source address, destination address were preserved during merging. The average packet size of the resulting traffic file was 500 bytes. The trace file had around 6000 unique source addresses and 6000 unique destination addresses. Care was taken during merging to ensure that the traffic of the appropriate load was generated. In contrast to all the previously described results, in this case codewords were allocated to individual addresses. Where codewords were insufficient, codeword reuse was allowed. The results how a slight improvement in network throughput. The improvement is due to the squeeze through effect [6]. This effect is because interference results in a lower packet error rate for shorter packets. This can result in an overall higher packet throughput if the fraction of short packets is high.

VII. Related work

The most well studied state estimation mechanism for contention protocols is the Carrier Sense Multiple Access (CSMA) mechanism. Carrier sensing [8] is a mechanism by which nodes first sense the medium to ensure that the medium is free before transmitting. [9] provides a detailed discussion of how carrier sensing is implemented in a wireless network and how it can improve throughput. Another form of state estimation for wireless networks is multi-user interference estimation. Multi-user interference estimation is used to estimate interference levels in wireless networks. [10] uses a multi-timescale interference predictor to predict the occurrence of interference. Depending on the level of interference, rate and admission control are used to control transmissions on the network. The time scales at which these algorithms work is usually on the order of seconds (1 sec) and depends on the self similar nature of traffic. In contrast state estimation makes no assumption on traffic characteristics and operates on smaller time scales. Channel load sensing [11], [12], [13] is a packet radio system where nodes sense the channel load and refrain from transmitting if the load exceeds a threshold. The load is measured by estimating the number of simultaneous transmissions based on noise levels. The low coherence of state means that throughput cannot be improved

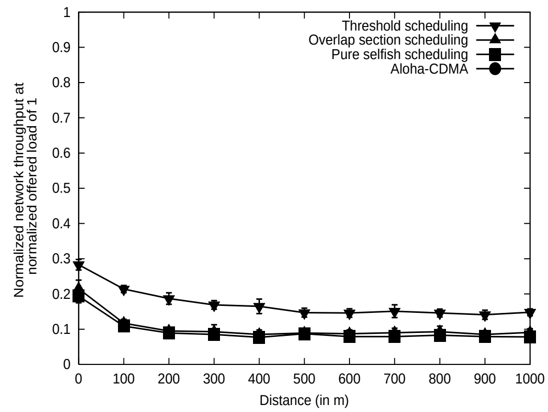

Fig. 16. The graph shows normalized network throughput vs. average distance from coupler (uniform distribution) for the transmission scheduling algorithms and on-demand state estimation. The results are based on simulation. The codeset length is 10. All other parameters are specified in Table II

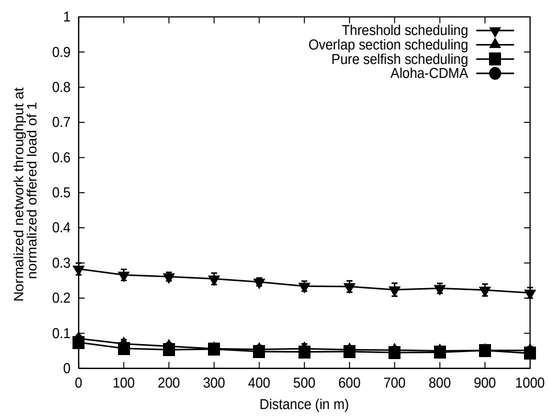

Fig. 17. The graph shows network normalized throughput vs. average distance from coupler (uniform distribution) for the transmission scheduling algorithms and on-demand state estimation. The results are based on simulation. The codeset length is 100. All other parameters are specified in Table II

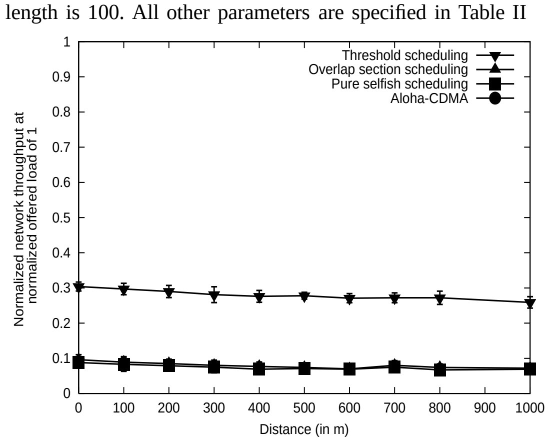

Fig. 18. The graph shows network normalized throughput vs. average distance from coupler (uniform distribution) for the transmission scheduling algorithms and on-demand state estimation. The results are based on simulation. The codeset length is 200. All other parameters are specified in Table II

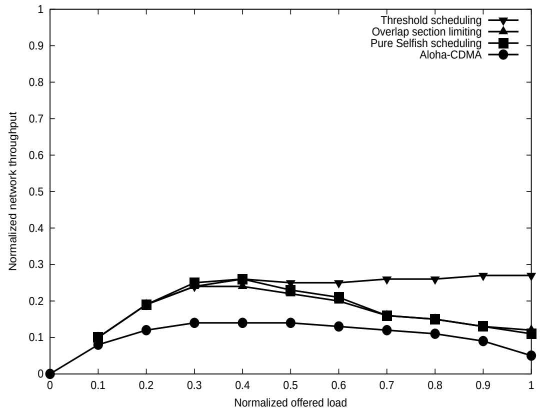

Fig. 19. The graph shows normalized network throughput vs. normalized offered load for the transmission scheduling algorithms and on-demand state estimation with realistic network traffic. The results are based on simulation. All other parameters are specified in Table II

through transmission scheduling. Adireddy [14] proposed a decentralized access protocol for wireless networks called *transmission control* which uses channel state information to schedule packet transmissions. The channel state is a scalar variable calculated by the receiver and sent to the transmitter. The channel state is used to calculate the probability with which a node should transmit a packet in the next slot. The low coherence of state in the wireless medium means that pre-transmission coordination (communication between receiver and transmitter) is needed for accurate state estimation.

VIII. Conclusions and future directions

The main contribution of this work is the analysis of algorithms for state estimation. Prior to this work, little work had been done in the area of media access control for optical CDMA. This work showed that the state of an optical CDMA network exhibits the property of *coherence*. This property was exploited to design state estimation. The study demonstrates that when all the configurable parameters (codeset, transmission scheduling and state estimation) are chosen correctly, throughput collapse under high offered load can be prevented.

An open area of research is to understand the effect of errors in the state observation process. Estimation algorithms of lower complexity then sample means which can reduce the impact of errors due to collisions may exist and may enable the gap between realistic and perfect state estimation to be bridged further. The joint design of the optical and electronic components of state estimation hardware is also an area for research.

References

[1] B. Mukherjee, "WDM based local lightwave networks. Part I: Single hop systems," *IEEE Network Magazine*, vol. 6, no. 3, pp. 12–27, May 1992.

[2] A. Keshavarizian and J. A. Salehi, "Optical orthogonal code acquisition in fiber optic CDMA systems via simple search method," *IEEE Transactions on Communications*, vol. 50, no. 3, pp. 473–483, March 2002.

[3] H. Chung, J. Salehi, and V. K. Wei, "Optical orthogonal codes: Design, analysis, and applications," *IEEE Transactions on Information theory*, vol. 35, no. 3, pp. 595–605, May 1989.

[4] O. Moreno, Z. Zhang, P. Kumar, and V. Zinoviev, "New constructions of optimal cyclically permutable constant weight codes," *IEEE Transactions on Information Theory*, vol. 41, no. 2, March 1995.

[5] J. Salehi, "Code division multiple-access techniques in optical fiber networks - Part 1: Fundamental principles," *IEEE Transactions on Communications*, vol. 37, no. 8, pp. 824–833, Aug. 1989.

[6] P. Kamath, J. D. Touch, and J. A. Bannister, "Algorithms for transmission scheduling in optical CDMA networks," *Under submission*, 2006.

[7] A. Allen, *Probability, statistics and queueing theory with computer science applications*. Academic Press, 1990.

[8] F. A. Tobagi and V. B. Hunt, "Performance analysis of carrier sense multiple access with collision detection," *Computer Networks*, vol. 4, no. 5, pp. 245–259, Oct. 1980.

[9] K. Jamieson, B. Hull, A. K. Miu, and H. Balakrishnan, "Understanding the Real-World Performance of Carrier Sense," in *ACM SIGCOMM Workshop on Experimental Approaches to Wireless Network Design and Analysis (E-WIND)*, Philadelphia, PA, August 2005.

[10] J. Zhang, M. Hu, and N. B. Shroff, "Bursty traffic over CDMA: Predictive MAI temporal structure, rate control and admission control," *Computer Networks Journal*, vol. 42, no. 6, pp. 779–796, Aug 2003.

[11] A. H. Abdelmonem and T. N. Saadawi, "Performance analysis of spread spectrum packet radio network with channel load sensing," *IEEE Journal on Special Areas in Communications*, vol. 7, no. 1, pp. 161–166, Jan. 1989.

[12] G. Judge and F. Takawira, "Spread Spectrum CDMA Packet Radio MAC Protocol using Channel Overload Detection and Blocking," *Wireless Networks*, vol. 6, pp. 467–479, December 2000.

[13] K. Toshimitsu, T. Yamazoto, M. Katayama, and A. Ogawa, "A novel spread slotted Aloha system with channel load sensing protocol," *IEEE Journal on Special Areas in Communications*, vol. 12, no. 4, pp. 665–672, May 1994.

[14] S. A. Reddy and L. Tong, "Exploiting decentralized channel state information for random access," *IEEE Transations on Information Theory*, vol. 51, no. 2, pp. 537–561, Feb. 2005.