Scheduling Methods for Multi-User Optical Wireless Asymmetrically-Clipped OFDM

Sarah Kate Wilson and JoAnne Holliday

Abstract: **Diffuse optical wireless (DOW) systems have the advantage that they do not require point-to-point siting so one transmitter can communicate with several receivers. In this paper, we investigate multiple access scheduling methods for downlink orthogonal frequency division multiplexing (OFDM) in diffuse optical wireless networks. Unlike the radio frequency (RF) channel, the DOW channel has low-pass filter characteristics and so requires different scheduling methods than those developed for the RF channel. Multi-user diversity orthogonal frequency division multiple access (OFDMA) systems nominate a cluster of subcarriers with the largest signal-to-noise-ratio for transmission. However, in a DOW channel, most users would choose the lowest frequency clusters of subcarriers. To remedy this problem, we make two proposals. The first is to use a variable cluster size across the subcarriers; the lower frequency clusters will have fewer subcarriers while the higher frequency clusters will have more subcarriers. This will equalize the capacity of the clusters. The second proposal is to randomize a user's cluster selection from a group of clusters satisfying a minimum threshold. Through simulation it is shown that combining these strategies can increase the throughput while ensuring a fair distribution of the available spectrum.**

Index Terms: **Diffuse optical wireless (DOW) communications, intensity modulation, orthogonal frequency division multiple access (OFDMA), orthogonal frequency division multiplexing (OFDM), scheduling.**

I. INTRODUCTION

Wireless systems operating at optical frequencies are an attractive alternative to radio-frequency (RF) based wireless local area networks (WLANs) for several reasons. In particular, optical wireless transmission requires no licensing, has greater privacy and presents no RF radiation issues. Diffuse optical wireless (DOW) systems are useful in multi-user scenarios as they need no siting. DOW systems using orthogonal frequency division multiplexing (OFDM) provide an alternative modulation for WLANs [1]–[3]. Optical wireless OFDM can provide flexibility when multiple users are present due to its time-frequency grid as found in other orthogonal frequency division multiple access (OFDMA) systems, e.g., [4].

A key issue in multi-user packet network systems is how to schedule users efficiently so that users with different quality-of-service requirements experience satisfactory service [5]–[7]. A second issue is that in a DOW channel, the signal is power-limited due to safety constraints. As such, determing available rates given a fixed power budget is an important concern. Scenarios where this scheme might be used include home networking as well as networking within a classroom or auditorium. In a home network, there might be up to 5 users; however, in a classroom, many users might be competing for the links. In addition, in a classroom, it is conceivable that there might be two access points for user access and an intelligent scheduler would turn away users that do not have sufficient signal to allow users with better signal access. The users whose signal is not strong enough to support their required data rate could possibly access the second or even third access point within a classroom situation.

The issue of how to schedule users over the time-frequency grid that OFDMA provides has been investigated for RF channels in among others [5]–[7]. In [5], ways to efficiently and fairly assign data rates to different users for a fixed power allocation were investigated. Feedback was minimized and multi-user diversity [8] was exploited in the following way. Rather than have each user feedback the signal to noise ratio (SNR) on every subcarrier, each user would send the controller the index of a cluster of contiguous subcarriers that had the maximum metric, where the metric was based on a combination of the SNR and the amount of data the user had already transmitted or still needed to transmit. The SNR is a measure of possible throughput, while the amount of data remaining is a measure of fairness.

However, these methods were designed for RF channels where the SNR of a given subcarrier can vary widely across the allocated frequency band. This is not the case in DOW channels that act as low-pass filters [1], [9], [10]. In an RF scenario, if there are 10 available clusters of subcarriers and each user selects its cluster with the maximum SNR, the probability that three users will pick the same cluster is quite small. However, in a DOW channel, the smaller frequencies, on average, have the largest SNR. If every user selects the cluster of subcarriers with the largest SNR, there will very likely be a collision and loss of data.

To solve this problem we present a scheduling technique for asymmetrically-clipped optical OFDMA (ACO-OFDMA) that takes into account the low-pass filter nature of the channel. In addition to increasing total network throughput, a network operator would want to ensure that as many users as possible can achieve their *desired* rate. To achieve this goal in a DOW channel, a scheduling algorithm that intelligently randomizes the cluster selection is proposed and evaluated.

The structure of this paper is as follows. In Section II, the scenario for this multiple access system is presented. In addition, a probabilistic analysis of using maximum SNR in a DOW channel is presented. In Section III, two ways to modify OFDMA

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S. K. Wilson is with the Department of Electrical Engineering, Santa Clara University, Santa Clara, CA 95053, USA email: skwilson@scu.edu.

J. Holliday is with the Department of Computer Science and Engineering, Santa Clara University, Santa Clara, CA 95053, USA, email: jholliday@scu.edu.

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selection for the DOW channel are presented: Varying the cluster size based on its relative value in the spectrum and a semi-random method for cluster selection. Section IV presents simulations that show how the proposed method compares to some RF OFDMA methods as well as time division multple access (TDMA) scheduling methods. Section V summarizes the previous results.

II. SCENARIO AND ANALYSIS

A. Scenario

For the downlink of a DOW OFDM system, the channel can be modeled as the sum of a set of positive taps.

$$h(t) = \sum_{n=0}^{N_t-1} \alpha_n \delta(t - \tau_n) \quad (1)$$

where $\alpha_n > 0$ represents the attenuation of the channel, τ_n the tap delay, and N_t is the number of taps. In [10], the DOW channel is modeled as either an exponentially decaying channel or a ceiling bounce model. Both the exponential decay model and the ceiling bounce model are parameterized by the delay spread, τ_{DS} of the channel which in turn depends on the size and construction of the room. In the exponential decay model, the amplitude

$$\alpha_n \propto \exp\left(-\frac{\tau_n}{\tau_{\mathrm{DS}}}\right) \quad (2)$$

while in the ceiling bounce model,

$$\alpha_n \propto \frac{6a^6}{(\tau_n + a)^7} \quad (3)$$

where $a = 12\tau_{\mathrm{DS}}\sqrt{11/13}$. In both cases, the amplitudes decrease as the delay increases, due to the attenuation of the light over longer paths. Whether the modulation is direct current (DC)-biased or ACO-OFDM, the received data on each subcarrier will have the form.

$$Y_k = H_k c_k + v_k$$

where c_k is the constellation value on the kth subcarrier, H_k is the Fourier transform of the time-domain signal $h(t)$ at frequency k/T_s where T_s is the length of the OFDM symbol (without the cyclic prefix), and v_k is an additive Gaussian white noise. Note that because all the channel taps are real and positive, the first subcarrier $|H_0|^2$ will have the largest power over all other subcarriers. For this scenario, we assume no power control and that the maximum SNR of any one user is 20 dB.

In [5], a scheduling method for OFDMA for RF channels was introduced that minimized feedback while ensuring fairness and appropriate quality-of-service to each user. In that scheme, each user sent back the cluster index that contained the subcarriers with the highest SNR. This will not work in a DOW OFDMA system. This is because each user, on average, would return its lowest frequency cluster, leading to scheduling conflicts and inefficient use of available spectrum.

B. Analysis

When scheduling users in an OFDMA system, there are some questions that should be considered.

1) What percent of the available spectrum is being used?
2) What information does the scheduler need to use the available spectrum efficiently while ensuring that the greatest number of users achieve their desired rate?

If only a fraction of the available spectrum is assigned to users in the system, that is an indication that part of the spectrum has been wasted.

In [5], an analysis of the expected number of occupied clusters for OFDM was presented and given by

$$\frac{1}{N_c} E[U_k] = \frac{1}{N_c} \sum_{u=S}^{N_c} u P(U_k = u) \quad (4)$$

where N_c is the maximum number of clusters in the OFDMA symbol, U_k is the number of clusters that are occupied by K users, $P(U_k = u)$ is the probability that K users occupy u clusters, and S is the number of candidate clusters that each user feeds back. As such, if $S = 2$, a minimum of two clusters in the OFDMA symbol will be occupied by user data. For example, if two users request the same cluster, then $U_2 = 1$, but if 2 users request two different clusters, then $U_2 = 2$.

The higher the expected number of occupied clusters, the more efficient the use of the spectrum. In RF OFDM systems, the analysis is rather straightforward as the presumption is that all the clusters on each user's OFDM signal have an equal probability of being used. However, in the DOW channel which acts as a low-pass filter, each cluster has an unequal probability of being chosen: Typically the lower frequency clusters have a higher probability of being selected than the higher frequency clusters due to the higher SNR on those clusters.

In the Appendix, the probability of expected cluster usage is expanded for the case of unequal cluster selection probabilities. To calculate those selection probabilities, channel statistics were simulated using both the exponential model (2) and the ceiling bounce model (3) for root mean square (RMS) delay spreads varying between 2 and 20 ns. Assuming 3 ns sampling periods and 128 possible tones with 8 clusters, 4 subcarriers per cluster, it was found that the probability that the lowest frequency cluster has the maximum SNR is 1, and the probability that the next lowest frequency cluster has the next highest value is approximately 0.9. If users request to send data on their largest SNR cluster, they will always request the lowest frequency cluster. With a very high probability, they will request the second lowest frequency cluster as their second choice. The expected number of occupied clusters of such a system was computed using (4) for the case of 8 clusters and is shown in Fig. 1. Each user can request 2 clusters and only 1 user can occupy a cluster at a time. To compute the probability for the DOW channel, the probability was simplified by assuming that the remaining 6 clusters had an equal probability of being chosen while the lowest frequency cluster was chosen with probability 1 and the next lowest with probability 0.9. As a comparison, we included the expected number of occupied clusters for the RF channel where the probability a cluster is chosen using the maximum SNR criteria is uniformly distributed.

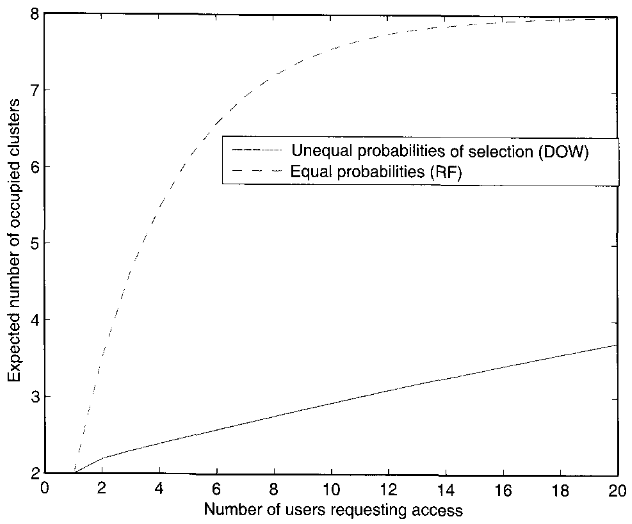


Fig. 1. The expected number of clusters that will be occupied in an OFDMA signal with 8 clusters and each user requesting 2 clusters.

As seen in Fig. 1, the metric for choosing clusters that works in RF channels will not result in efficient spectral usage in the DOW channel, due to the unequal SNR probability inherent in the DOW channel. Note that even when the cluster SNR probability is uniformly distributed (the RF case), the expected spectral usage does not reach 100% until more than 16 users (twice the number of available clusters) request access to the system; but this is still more efficient than the case of the DOW channel, where the cluster SNRs are not uniformly distributed.

This analysis indicates that basing cluster selection on the maximum SNR will result in excessive collisions and inefficient use of the spectrum. Though random cluster selection results in a larger spectrum use, a random cluster selection algorithm may not be appropriate for the DOW channel for the following reason. Randomly selecting a cluster may minimize possible collisions but result in a cluster selection that is not able to carry the requested user's data rate. For scheduling in the DOW channel to result in efficient channel use, there should be some randomization of cluster selection as long selected clusters have sufficient SNR to carry the requested rate.

Our solution is to have each user determine which available clusters have sufficient SNR to achieve its desired throughput. The user then randomly selects one of the clusters with sufficient SNR, i.e., each user is choosing spectral resources according to its need. It will not necessarily maximize the possible throughput of the system as multi-user diversity does in an RF system. However, it ensures that a user will only choose clusters that are sufficient for transmitting its data. Note that if a user only has a small amount of data, the threshold for choosing a cluster set is much lower and the user has a wider selection to choose from. A high-data rate will have a larger threshold and is more likely to select lower frequency clusters. By having the user pick a threshold for cluster selection, it ensures that if the user receives all of its requested clusters, it can achieve it's desired bit rate. In addition, some users may have a larger over-all SNR, e.g., they may be closer to the transmitter than other users. As such, they will choose from a larger set of clusters than those with smaller overall SNRs. By properly choosing parameters, more of the available spectrum will be used.

We have simplified and reduced the amount of feedback by having each user send to the scheduler information about only S out of N_c available clusters [5]. By first identifying the clusters that can carry the desired data rate, then randomizing the selection among those candidate clusters, a more efficient use of the spectrum in terms of throughput and user satisfaction can be gained. The scheduler considers both the SNR of a given user's cluster and the amount of data remaining in a user's queue when resolving a conflict [11], [12]. If two or more users request the same cluster, the scheduler chooses the user with the largest metric

$$\text{User metric} = \sum_{k \in \text{UserCluster}} \log_2(1 + \text{SNR}_k) Q_R \qquad (5)$$

where Q_R is the amount of data left in a user's queue. As a user's queue length increases, it will be more likely to win a cluster slot in the case of a collision, i.e., two or more users requesting the same slot. Queue-based scheduling is a way to maximize the throughput of the system while making sure that no user's queue grows too large and thus ensuring some fairness in the system.

Of course, another way to schedule users is to give each user the entire spectrum, and schedule according to the metric in (5) where the set UserCluster includes all the available subcarriers, i.e., TDMA. We compare our OFDMA approach to a TDMA approach in the Section IV. Depending on the user needs and the SNR spread among the users, a TDMA approach is a viable alternative to OFDMA.

III. SCHEDULING ALGORITHM FOR THE DOW CHANNEL

We propose the following two methods for ensuring a fair allotment of the subcarriers among the users. First, because we know that the lower frequency clusters will have, on average, a larger SNR and hence a larger bit rate, we change the size of the clusters, putting fewer subcarriers in the lower frequency clusters and more subcarriers in the higher frequency clusters. Second, rather than have a user propose its best cluster, it will select a random cluster among those that are above its required SNR threshold for achieving its desired rate.

In a DOW channel, if every user requests transmission on its cluster of subcarriers with the best average SNR, it is most likely that every user will request the same cluster, the lowest-frequency cluster of subcarriers. This is because the wireless optical channel acts as a low-pass filter and we know that the DC term will have the largest SNR. The resulting "collision" means that many users will not have access to that OFDM signal. The fact that the lower frequency clusters have larger SNRs than the higher frequency clusters can be mitigated by changing the cluster size. If the cluster size of the lower frequency subcarriers is decreased while the cluster size of the larger frequency subcarriers is increased, the SNR's for each cluster are more consistent. However, depending on the channel itself, it is not straightforward to choose a fixed cluster size that will ensure an even distribution of SNR's across the users' clusters. In addition, if each user has a similar delay spread (as they are in the same room), the cluster distribution may be similar across different users. For example, with a redistributed cluster size, if the fifth cluster is the best for user 1, it may also be the best for user 4 as both users share similar power delay profiles. This means that changing the cluster size is not enough to ensure that the entire spectrum is used efficiently.

To ensure fair distribution of the given spectrum and minimize the number of users requesting the same cluster, we propose the following scheduling algorithm called "semi-random." Each user performs the following actions.

1) For each cluster, estimate its data rate:

$$R(i,u) = \sum_{k \in N_i} \log_2(1 + \mathrm{SNR}_{k,u}) \quad (6)$$

where N_i is the set of indices of the ith cluster and $R(i,u)$ is the rate that can be supported by the ith cluster and the uth user. Note that the rate depends on both the size of the cluster N_i as well as the SNR on each subcarrier within the cluster. Note that the rate estimate can be made more conservative by decreasing the SNR in the log by a gap factor, Γ [13].

2) Each user finds all clusters whose estimated rate $R(i,u)$ is greater than the user's desired rate $D(u)$.

3) A user picks S clusters randomly from the eligible set. In the simulations shown later in this paper, this was done by using a uniform random number generator to pick an index from the available set. Note that some users may not have any clusters above the threshold and so this user will not transmit any data. This prevents a user with low SNR from using valuable spectrum when another user, with sufficient signal strength, could use that spectrum more effectively. However, if there is only one user in the system, the threshold or the number of requested clusters can be adjusted.

4) The user transmits the indices and the SNR of the cluster to the transmitter. If more than one user requests the same cluster, the transmitter chooses the user with the highest queue and SNR on that subcarrier as in (5).

Note that in a DOW channel, imperfect channel state information (CSI) is much less of a concern than it would be in an RF channel, as the intensity-based modulation will change at the rate that objects or the receiver move in the environment. This means that it will not have the high Doppler characteristics of, say, a 60 GHz carrier frequency, as it is a baseband-modulated technique. As such, increasing the required SNR to send a specific number of bits is less crucial in this system than it would be in a fast-fading environment where the CSI may be outdated by the time transmission occurs.

The advantage of this method is that when there is a variety of user data rates, the randomization across appropriate subcarriers provides a way to divide the spectrum fairly. It is not traditional multi-user diversity, as we are not sending the best cluster for each user. In addition, we are not sending clusters if a user's SNR is not strong enough. A user with poor SNR will not use valuable resources when its signal strength is not strong enough to support it's data rate. These users would be better served by another node in the system and prompts the idea of a multi-base-station optical wireless system.

IV. SIMULATIONS

In this section, we present the results of the simulation of our proposed methods and compare them to the maximum SNR approach used for RF, TDMA, round-robin, and TDMA with the metric given in (5). In summary, the following six approaches are simulated.

1) TDMA approaches:
   a) Choose the user with the largest user metric, assuming one cluster per OFDM symbol.
   b) Round-robin scheduling.
2) OFDMA approaches:
   a) Each user chooses $S = 2$ random clusters with an SNR above threshold (semi-random method).
   b) Each user chooses $S = 2$ random clusters without considering a threshold value (random approach).
   c) Each user sends the $S = 2$ clusters with the maximum SNR (maximum SNR method).
   d) Each user sends the SNR of all clusters to the scheduler.

In all the OFDMA methods, the scheduler resolves conflicts when two or more users request the same cluster by choosing the user with the highest metric, as given in (5) for that cluster.

The TDMA approaches have the advantage that they are simple, and that they use the entire available spectrum. In the largest metric case, all users send one value, their bit capacity multiplied by their existing queue. The user with the largest metric is scheduled. The round-robin approach is ultimately very fair, but does not take into account either the user's desired bit rate or their achievable rate.

The OFDMA approaches have the advantage that they divide the available spectrum into a grid. This allows multiple users to share spectrum. We include in our comparison a random OFDMA method to show the effectiveness of a threshold. The third approach, feeding back the maximum two clusters, is the RF-based multi-user diversity approach. The fourth method, feeding back all clusters and letting the scheduler resolve the conflict is the most complex method and has the most overhead but is included to show the maximum performance that can be achieved when the scheduler has complete information about each user's set of clusters. The simulation parameters are summarized in Table 1. The simulations are based on the average of 5000 different channel trials. The channels were generated randomly using both the exponential and the ceiling bounce model, each model was used 50% of the time. To generate a variety of channels, the channel taps α_n, as shown in (1) were uniform random variables whose amplitude varied from 0 to $\exp(-\tau_n/\tau_{\mathrm{DS}})$ for the exponential distribution as in (2); and between 0 and $6a^6/(\tau_n+a)^7$ where $a = \sqrt{(11/13)}12\tau_{\mathrm{DS}}$ for the ceiling bounce model as in (3). In each trial, each user's channel was multiplied by a uniform random variable so that each user had different signal strengths. Given the SNR of each subcarrier, each user's average SNR for an ACO-OFDM was measured to be

$$\mathrm{SNRavg} = \frac{4}{N} \sum_{k=0}^{\frac{N}{4}-1} \frac{|H_{2k+1}|^2}{\sigma^2}$$

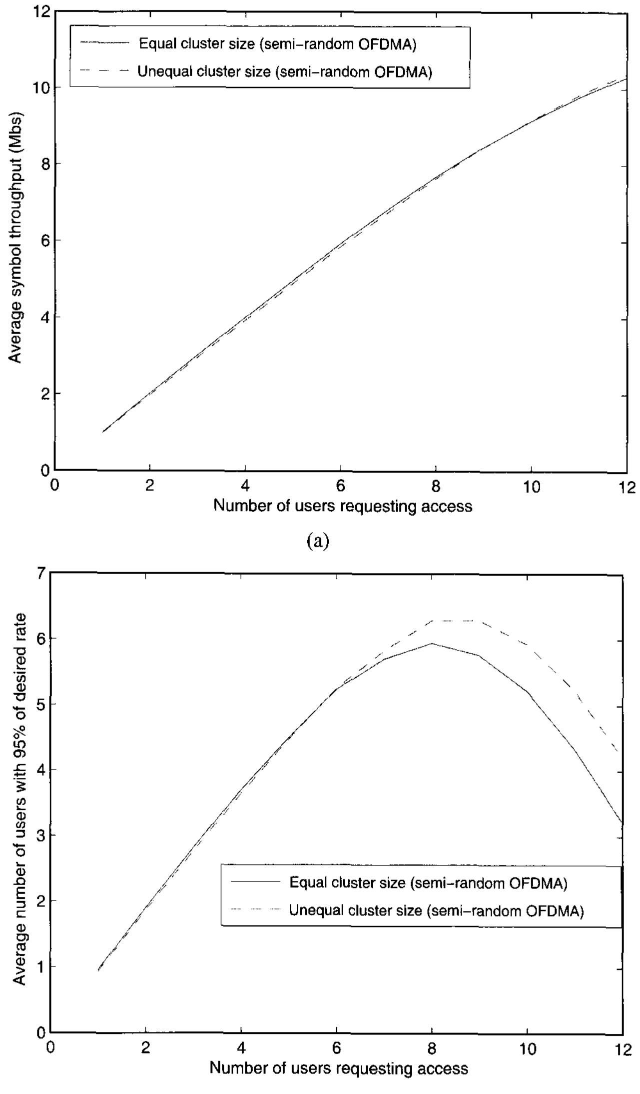
where $|H_{2k+1}|^2$ is the squared absolute value of the frequency response of subcarrier $2k+1$, and σ^2 is the variance of the noise.

Table 1. Simulation parameters.

ACO-OFDM characteristics	
Number of subcarriers	128
Number of modulated subcarriers	32
Number of samples in cyclic prefix	8
Sample size	3 ns
OFDM symbol period	480 ns
Number of subcarrier clusters	8
Cluster allocation (equal size)	4 subcarriers per cluster
Cluster allocation (different size)	$[2, 2, 3, 3, 5, 5, 6, 6]$ subcarriers per cluster
Data rates	
Requested rate	4 Mbps
Requested average rate per OFDMA symbol per user	2 bits
Frame size and length of simulation	
Size of frame	1 OFDM symbol
Number of frames per average	500
Percent of data required to count a user	95%
Number of different channels per point	5000
Channel information	
Maximum number of taps in channel	64
Tap spacing	0.75 ns
Channel model	Used both ceiling bounce and exponential [10] with delay spread
Exponential	$(1/\tau_{\mathrm{DS}})\exp(-t/\tau_{\mathrm{DS}})u(t)$
Ceiling bounce	$\frac{6a^6}{(t+a)^7}u(t)$ where $a = 12\sqrt{\frac{11}{13}}\tau_{\mathrm{DS}}$.
Delay spread	Randomly chosen between 0.2 and 7 ns for each channel
SNRs	Ranged from -25 to -2 dB.

Because ACO-OFDM only modulates the odd subcarriers and the subcarrier constellations must be Hermitian symmetric to ensure a real positive signal [3], only one quarter of the N available subcarriers are used. For this reason, the average SNR only considers $N/4$ of the subcarriers. For multiple users the average SNRs ranged from -25 to -2 dB. For each trial, the range of average SNRs among different users was generally less than 10 dB.

Two metrics were used to evaluate the performance. The first metric is the average normalized throughput of the cell which is limited by user data requests. For example if no user requests access, the throughput is zero. If one user requests 1 Mbs, and the signal can support 2 Mbs, the throughput is calculated at 1 Mbs; if one user requests 1 Mbs, but the system can only support 0.8 Mbs, the throughput is calculated as 0.8 Mbs. The throughput metric is driven by the user requests and the capacity of the system.



(a)

(b)

Fig. 2. Plots of rate and the number of users serviced when each user requests 1 Mbs. Fig. 2(a) shows the cumulative rate of the OFDM symbols as more users enter into the system. Fig. 2(b) shows the number of users who achieve at least 95% of their desired rate. In all the OFDMA schemes, but the maximum cluster one, each user is requesting two clusters

The second metric is the number of users who achieve 95% or higher of their desired rate. This metric specifies how well each user is being served. We call these users, "satisfied" users. For example, there could be a method that has a network throughput of 0.1 bits/sec/Hz, but no user achieves more than 10% of its desired rate. Another method could have an average throughput of 0.08 bits/sec/Hz, but five users may achieve 95% of their desired rate. The second metric measures the number of customers that the system could support. Fig. 2 shows the effect of changing the cluster size from 4 subcarriers per cluster to the unequal cluster size given in Table 1. Changing the cluster size can increase

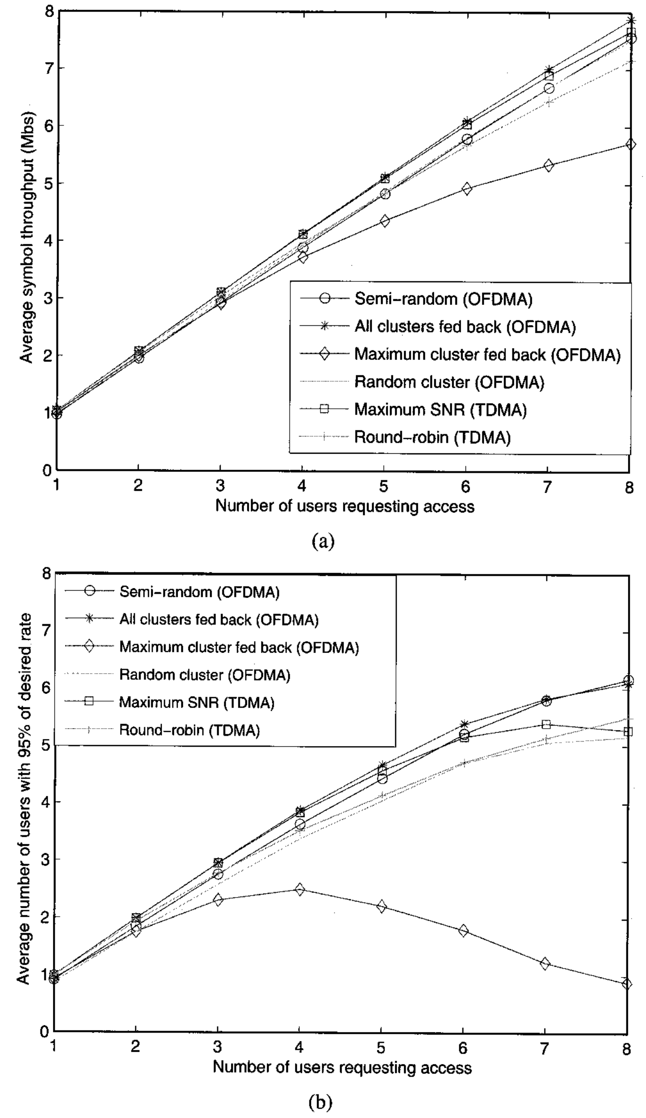


Fig. 3. Plots of rate and the number of users serviced when each user requests 1 Mbs. Fig. 3(a) shows the cumulative rate of the OFDM symbols as more users enter into the system. Fig. 3(b) shows the number of users who achieve at least 95% of their desired rate. In all the OFDMA schemes, but the maximum cluster one, each user is requesting two clusters.

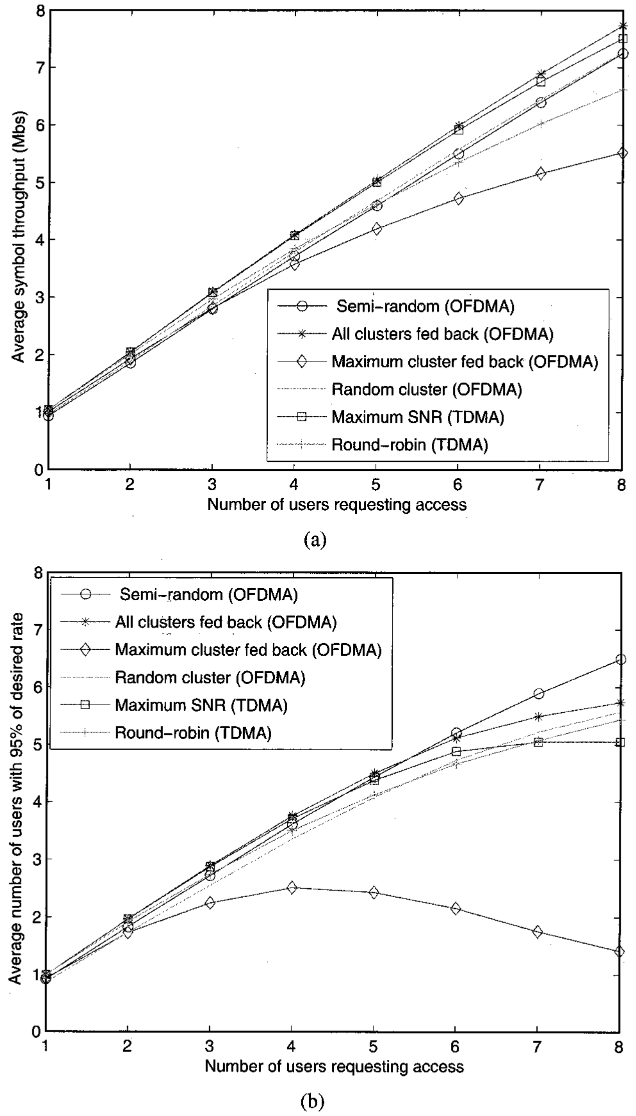
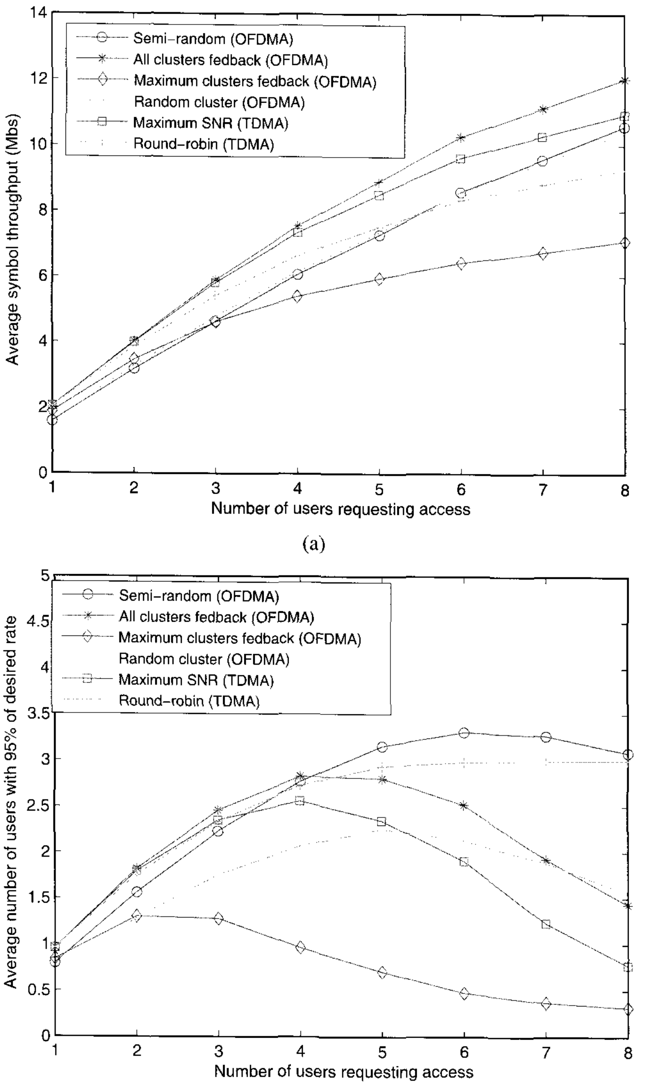


Fig. 4. Plots of rate and the number of users serviced when each user has a different rate request. Desired rates range between 0 and 2 Mbs per second. Fig. 4(a) shows the cumulative rate of the OFDM symbols as more users enter into the system. Fig. 4(b) shows the number of users who achieve at least 95% of their desired rate. In all the OFDMA schemes, but the maximum cluster one, each user is requesting two clusters.

the number of users who achieve their desired rate, but in this case there is little effect when the number of users requesting access is less than 6 when 8 clusters are available. Note that as the number of users requesting access increases, the number of "satisfied" users decreases because too many users are requesting a limited amount of spectrum. Spreading this limited access among several users results in fewer users achieving their desired rate, though the average throughput will increase as more users request access.

Figs. 3, 4, and 5 show the average throughput and the average number of users served as a function of the number of users requesting access. While in Fig. 3, each user is requesting 1 Mbs. In Fig. 4 users' requested rates can vary between 0 and 2 Mbs and in 5, users' requested rates vary between 0 and 4 Mbs.

It should not be surprising that the average throughput of maximum SNR scheduling is less than either the proposed semi-random threshold method or even the maximum metric TDMA method. When multi-user diversity is used in an RF channel, we take advantage of the natural randomization of the SNR. In an optical wireless channel that natural randomization is not there, so we must introduce a different form of randomization of the cluster selection to ensure fewer collisions and more scheduled users. In addition, the random clusters above the threshold method will not schedule users whose SNR is too low to give the user its desired rate. The maximum SNR cluster OFDMA method has the worst performance of all six methods. As the number of users requesting access increases, the number of users who achieve their desired rate decreases. In addition, though the average throughput increases with each additional user, the marginal increase in benefit to each user goes down. The reason the number of users who achieve their desired



(a)

(b)

Fig. 5. Plots of rate and the number of users serviced when each user has a different rate request. Desired rates range between 0 and 4 Mbs per second. Fig. 5(a) shows the cumulative rate of the OFDM symbols as more users enter into the system. Fig. 5(b) shows the number of users who achieve at least 95% of their desired rate. In all the OFDMA schemes, but the maximum cluster one, each user is requesting two clusters.

bit rate decreases as the number of users increase is because the users are competing for limited spectrum. This is also a drawback of the round robin scheduling which also stresses the network with under-performing users. Ideally, the user whose SNR is too low, would be scheduled by another network node where the SNR will be better. This leads to the idea of having multiple transmitter points in a room to improve performance.

In general, when the number of users requesting access is less than 5, the best method in terms of both throughput and satisfying the largest number of users is OFDMA where each user sends back information about all its clusters. In general, this technique has the largest throughput of any of the proposed methods. The scheduler has information about every user and every cluster and can distribute the available clusters accordingly. This has a higher overhead in terms of required feedback, but because the channel will change very slowly this amount of feedback may be feasible in some situations. However, as the number of users increases, users with lower SNRs will have less access, as the higher SNR subcarriers with the highest queue will prevail. With the semi-random OFDMA method, because each user only requests two clusters each, there is a larger probability that a cluster will be available for a user with a lower SNR that is still strong enough to support the requested data rate. This scheduling method achieves both fairness and efficient throughput. This becomes even more apparent in Fig. 5. In this set of simulations, the data rates can be higher and the semi-random has the highest number of users who achieve their desired rate, even though it's total throughput is not as high as the all clusters OFDMA or the maximum SNR TDMA scheduling method.

TDMA scheduling, where the user with the highest metric, as in (5), uses the whole OFDM symbol, works relatively well especially when all users have the same required data rate. When the data rates are different, TDMA is less successful in ensuring user data rates as the number of users increases.

The "random OFDMA" curves show the performance of a scheme where two clusters are selected by the user randomly without a threshold. The performance is comparable to round-robin TDMA. Neither method considers the SNR of the cluster when requesting access, though the "random OFDMA" method will resolve conflicts based on the metric (5).

As the number of users increases or the requested data rates increase, all methods will eventually have no users who achieve their desired rate. This trend can be seen in Fig. 5. This is because the methods are designed to share the spectrum. If the number of users is limited, the maximum SNR OFDMA works reasonably well. If the data rates are comparable or the multiple users have similar SNRs, TDMA is an excellent choice.

V. CONCLUSIONS

Multi-user diversity scheduling techniques that work well in RF channels do not work for diffuse optical wireless systems using OFDM without significant modification. Unlike the RF channel where feeding back the maximum SNR clusters provides excellent user satisfaction and throughput, a modified approach adapted to the optical channel is required.

Our method will work best in a downlink scenario where all users are synchronized. In an uplink scenario, a guardband between clusters is necessary to minimize intercarrier interference due to lack of synchronization. Future work could include examining the role of the unused subcarriers in mitigating the intercarrier interference in this situation. This paper introduces ways to select clusters in an OFDMA-based ACO-OFDM system. Both changing the size of the clusters and randomizing the choice of clusters given a minimum SNR threshold will produce more satisfied users in a multi-user, queue-based selection system. In addition, the semi-random method requires less feedback than the maximum SNR method. TDMA is also an excellent choice when data rates among the users are comparable or the scenario is such that each user will experience a similar receiver SNR.

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APPENDIX

A. Probability of Cluster Usage

In [5], it was shown that given that a user could request S clusters at a time, with a maximum of N_c clusters, the probability that U_k clusters contain data, where k indicates the number of users is

$$\begin{pmatrix} P(U_k = S) \\ P(U_k = S+1) \\ \vdots \\ P(U_k = N_c) \end{pmatrix} = \mathbf{A} \begin{pmatrix} P(U_{k-1} = S) \\ P(U_{k-1} = S+1) \\ \vdots \\ P(U_{k-1} = N_c) \end{pmatrix} \qquad (7)$$

where

$$\begin{pmatrix} P(U_1 = S) \\ P(U_1 = S+1) \\ \vdots \\ P(U_1 = N_c) \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

and

$$\mathbf{A} = \left(\mathbf{A}_1\, \mathbf{A}_2 \cdots \mathbf{A}_{\mathbf{N_c-S+1}} \right),$$

$$\mathbf{A}_1 = \begin{pmatrix} P(U_k = S | U_{k-1} = S) \\ P(U_k = S+1 | U_{k-1} = S) \\ \vdots \\ P(U_k = N_c | U_{k-1} = S) \end{pmatrix},$$

$$\mathbf{A}_2 = \begin{pmatrix} 0 \\ P(U_k = S+1 | U_{k-1} = S+1) \\ \vdots \\ P(U_k = N_c | U_{k-1} = S+1) \end{pmatrix},$$

$$\mathbf{A}_{N_c-S+1} = \begin{pmatrix} 0 \\ P(U_k = S+1 | U_{k-1} = S+1) \\ \vdots \\ 0 \\ P(U_k = N_c | U_{k-1} = N_c) \end{pmatrix}$$

i.e., the columns of the matrix $\mathbf{A}$ are the conditional probabilities of the number of clusters for k users given the number of clusters occupied by $k-1$ users.

For an RF OFDMA channel, one can assume that all clusters have equal probability of being the cluster with the maximum SNR and hence being chosen. So if a user can select $S = 2$ clusters at a time, and there are N_c possible clusters, finding the probabilities is a matter of counting the possible pairs. So for example, if $N_c = 8$ and $S = 1$, then

$$\mathbf{A} = \frac{1}{8} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 7 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 6 & 3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 5 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 & 7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 8 \end{pmatrix}.$$

If $N_c = 8$ and $S = 2$, then

$$\mathbf{A} = \frac{1}{28} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 12 & 3 & 0 & 0 & 0 & 0 & 0 \\ 15 & 15 & 6 & 0 & 0 & 0 & 0 \\ 0 & 10 & 16 & 10 & 0 & 0 & 0 \\ 0 & 0 & 6 & 15 & 15 & 0 & 0 \\ 0 & 0 & 0 & 3 & 12 & 21 & 0 \\ 0 & 0 & 0 & 0 & 1 & 7 & 28 \end{pmatrix}.$$

For a DOW channel, the probability that the lowest frequency cluster is the maximum is 1. If two clusters can be selected, then the important parameter is the probability a cluster having the second highest probability, say p_1, which is typically the second lowest frequency cluster. Because the probabilities a given cluster is chosen are not equal, the formulation in (7) is no longer valid.

We can simplify the analysis of the DOW by assuming that the probability the remaining clusters are chosen is $p_2 = (1 - p_1)/(N_c - 2)$. In this case, the conditional probabilities are more similar to the case of $S = 1$, as a user will always choose the lowest frequency cluster as one of the two clusters with variability only in the choice of the second cluster.

The probability of R clusters being chosen can be broken into two parts: The probability that the cluster with the larger probability $p(1)$ has been chosen by at least 1 user, $P_{p_1}(U_k = R)$, and the probability that this cluster has not been chosen by any other users, $P_{p_2}(U_k = R)$.

In this case,

$$\begin{pmatrix} P_{p_1}(U_k = 2) \\ P_{p_1}(U_k = 3) \\ \vdots \\ P_{p_1}(U_k = N_c) \end{pmatrix} = \mathbf{A}_1 \begin{pmatrix} P_{p_1}(U_{k-1} = 2) \\ P_{p_1}(U_{k-1} = 3) \\ \vdots \\ P_{p_1}(U_{k-1} = N_c) \end{pmatrix} + p(1) \begin{pmatrix} 0 \\ P_{p_2}(U_{k-1} = 2) \\ P_{p_2}(U_{k-1} = 3) \\ \vdots \\ P_{p_2}(U_{k-1} = N_c - 1) \end{pmatrix},$$

$$\begin{pmatrix} P_{p_2}(U_k = 2) \\ P_{p_2}(U_k = 3) \\ \vdots \\ P_{p_2}(U_k = N_c - 1) \end{pmatrix} = \mathbf{A}_2 \begin{pmatrix} P_{p_2}(U_{k-1} = 2) \\ P_{p_2}(U_{k-1} = 3) \\ \vdots \\ P_{p_2}(U_{k-1} = N_c - 1) \end{pmatrix},$$

$$\begin{pmatrix} P(U_k = 2) \\ P(U_k = 3) \\ \vdots \\ P(U_k = N_c) \end{pmatrix} = \begin{pmatrix} P_{p_1}(U_k = 2) \\ P_{p_1}(U_k = 3) \\ \vdots \\ P_{p_1}(U_k = N_c) \end{pmatrix}$$

$$+\begin{pmatrix} P_{p_2}(U_{k-1}=2) \\ P_{p_2}(U_{k-1}=3) \\ \vdots \\ P_{p_2}(U_{k-1}=N_c-1) \\ 0 \end{pmatrix}$$

and

$$\mathbf{A}_i = \left(\mathbf{A}_{i,1}\ \mathbf{A}_{i,2} \cdots \mathbf{A}_{N_c-S+1}\right),$$

$$\mathbf{A}_{i,1} = \begin{pmatrix} P_{p_i}(U_k=S|U_{k-1}=S) \\ P_{p_i}(U_k=S+1|U_{k-1}=S) \\ \vdots \\ P_{p_i}(U_k=N_c|U_{k-1}=S) \end{pmatrix},$$

$$\mathbf{A}_{i,2} = \begin{pmatrix} 0 \\ P_{p_i}(U_k=S+1|U_{k-1}=S+1) \\ \vdots \\ P_{p_i}(U_k=N_c|U_{k-1}=S+1) \end{pmatrix},$$

$$\mathbf{A}_{i,N_c-S+1} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ P_{p_i}(U_k=S|U_{k-1}=S) \end{pmatrix}$$

In particular,

$$\mathbf{A}_1 = \begin{pmatrix} p_1 & 0 & 0 & \cdots 0 \\ 1-p_1 & p_1+p_2 & 0 & \cdots 0 \\ 0 & 1-p_1-p_2 & p_1+2p_2 & \cdots 0 \\ & \vdots & & \\ 0 & 0 & 0 & \cdots 1 \end{pmatrix},$$

$$\mathbf{A}_2 = \begin{pmatrix} p_2 & 0 & 0 & \cdots 0 \\ 1-p_1-p_2 & 2p_2 & 0 & \cdots 0 \\ 0 & 1-p_1-2p_2 & 3p_2 & \cdots 0 \\ & \vdots & & \\ 0 & 0 & 0 & \cdots 1-p_1 \end{pmatrix},$$

$$\begin{pmatrix} P_{p_1}(U_1=2) \\ \vdots \\ P_{p_1}(U_1=N_c) \end{pmatrix} = \begin{pmatrix} p_1 \\ 0 \\ \vdots \\ 0 \end{pmatrix},$$

$$\begin{pmatrix} P_{p_2}(U_1=2) \\ \vdots \\ P_{p_2}(U_1=N_c-1) \end{pmatrix} = \begin{pmatrix} 1-p_1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}.$$

Note that the columns of A_2 will not sum to 1 as we are excluding the case where the cluster with probability p_1 is chosen.

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Sarah Kate Wilson earned her B.S. in Mathematics from Bryn Mawr College in 1979 and her M.S. and Ph.D. in Electrical Engineering from Stanford University in 1987 and 1994, respectively. She has worked in both academia and industry as a professor and as a research and development engineer. Her academic experience includes positions in Sweden as well as the United States. Her current research interests are in OFDM, wireless optical communications, and scheduling. She is currently an Assistant Professor in the Department of Electrical Engineering at Santa Clara University. She has served as an Associate Editor for IEEE Transactions on Wireless Communications, IEEE Communications Letters, IEEE Transactions on Communications, and the Journal of Communications and Networks. She is currently the Editor-in-Chief of IEEE Communications Letters and a Member-at-Large of the Board of Governors of the IEEE Communications Society.

JoAnne Holliday earned her B.S. degree in Physics from the University of California and her M.S. degree from Northeastern University. She received the Ph.D. in Computer Science from the University of California at Santa Barbara in August 2000. She joined the Faculty at Santa Clara University in September 2000 and is now a tenured Associate Professor of Computer Engineering. She is currently serving as Associate Editor for IEEE Communications Letters. Her research involves maintaining consistency in distributed systems and devising new energy efficient algorithms for ad-hoc and sensor networks. Her recent interests include peer-to-peer (P2P) networks and wireless 802.11 and cellular technology.