Power Allocation for Multi-band OFDM UWB Communication Networks

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Abstract— **Ultra wideband (UWB) technology has shown significant advantages over other existing ones for short- or medium-range high speed communications. It can adopt different modulation and signaling formats, among which multi-band OFDM is a more favorable candidate for the upcoming standard. Though extensive study on physical layer has been conducted, limited work exists in the literature on design of medium access control (MAC) layer protocols. This paper proposes an efficient low-complexity power allocation technique for clustered multi-band OFDM UWB networks. The idea is to assign a unique power for each cluster while maximizing the total throughput. The method shows much superiority to an existing framework that selects only the cluster with the highest quality each time. Its performance also approaches the standard water-filling scheme in many cases but with much reduced complexity. The method is tested for a mandatory $1.8GHz$ UWB band suggested in a standard proposal.**

I. INTRODUCTION

With recent release of a large spectral mask from $3.1GHz$ to $10.6GHz$ by the Federal Communications Commission [1], there emerges an increasing interest in studying UWB technologies for both commercial and military networks. A traditional UWB system adopts pulse position modulation and transmits trains of carrier-free time-hopping short-duration pulses with a very low duty cycle [2]. Thus such an impulse radio UWB technology offers high resolution in delay estimation and localization, excellent multipath mitigation in a dense multipath environment such as home networking, potentially high rate and low power transmission.

Impulse radio UWB is not the only signaling format to support UWB multiple access communications. The IEEE is undergoing a process of extensive discussions on UWB standard 802.15.3a (see for example [3]). Multi-band orthogonal frequency division multiplexing (OFDM) modulation format appears as a very competitive candidate [3], [4] due to its favorable properties to mitigate interference and achieve large throughput.

Up to date, most research works focus on transceiver design [5], [6], [7], channel characterization [8], [9] for impulse radio UWB systems. Little attention has been paid to medium access control (MAC) protocol design and corresponding study of effects from data modulation. Although power and rate assign techniques have been proposed for two different classes of traffic [10], namely reserved bandwidth and dynamic bandwidth, or a general framework is developed for scalable UWB network using a flexible cost function [11], they are designed for impulse radio UWB networks. Design of new MAC protocols for multi-band OFDM UWB systems appears imperative to accommodate emerging applications.

Power allocation is an integral part of MAC protocol design. For OFDM systems, it has been well-studied from various viewpoints. It is recognized that water-filling with adaptive modulation is the optimal solution if channel is static and known to the transmitter and receiver [12], [13]. In a downlink fading channel, an adaptive resource allocation method is proposed by maximizing the minimum capacity of all users for multiuser OFDM under a total transmit power constraint [14]. Instead, [15] considers total power minimization subject to data rate and full channel utilization constraints in order to find a solution for channel occupation, bit and power assignment of each subcarrier. The problem is solved after relaxing a requirement for integer variables to take real values. In fact, solution is obtained directly in [16] via integer programming. Transmit power can also be adapted according to maximization of the total data rate under constraints on total transmit power and bit error rate allowing sharing of subcarriers among users [17]. [18] adopts a flexible utility function to maximize with respect to subcarrier powers under a total power constraint.

In this article, a power allocation scheme for a clustered multi-band OFDM UWB network is proposed. In a multi-band OFDM UWB system, a chunk of bandwidth is divided into multiple sub-bands each with $528MHz$ bandwidth [3]. Users share them according to assigned time frequency codes. Within each sub-band, OFDM is employed, yielding 128 sub-carriers among which there are 100 data tones for information transmission, 12 pilot tones, 10 guard tones and 6 reserved NULL tones. Clustered OFDM is a promising technique for high-rate OFDM systems [19], [20], [21] where adjacent OFDM tones in each subband are further grouped into non-overlap clusters. The clustered OFDM not only maintains many nice properties of classical OFDM, but also offers some additional advantages such as in-band diversity gain, significantly reduced peak-to-average power ratio [19], and hardware simplicity [20].

For clustered multi-band OFDM UWB, a power assignment scheme is presented in [21] where only the cluster with the best channel condition is chosen to transmit signal each time. The method is claimed to be robust to multi-path fading. However its throughput is not optimized since only a small part of the bandwidth is used each time. When the channel approaches frequency non-selective, its performance may degrade a lot. Another method that can be applied for power allocation is the well-known optimal water-filling algorithm mentioned before. But it introduces too much complexity in a clustered OFDM system, since each subcarrier should adjust its power. We tradeoff performance and complexity, and propose an efficient low-complexity power allocation technique by assigning a unique power for each cluster while maximizing the total system throughput. It thus incurs less complexity than the water-filling approach, because only power for each cluster instead of each subcarrier needs to be adjusted. The method is tested for a mandatory $1.8GHz$ UWB band suggested in a standard proposal [3]. It shows much superiority to [21], and also approaches the water-filling scheme in many cases.

The rest of the paper is organized as follows. A clustered OFDM channel model is described in Section II. In Section III, the problem of maximizing throughput is brought out and corresponding solutions are given. Then numerical results achieved are shown in Section IV. Finally in Section V some conclusions are made.

II. SYSTEM MODEL DESCRIPTION

In this section we briefly present a clustered OFDM system model and frequency-fading channel model.

A. *Clustered Multi-band OFDM*

A clustered multi-band OFDM system is a particular type of a multi-carrier system where the transmitted bandwidth is divided into some narrow subchannels that are transmitted in parallel. As shown in Fig. 1, there are Q subbands and each of them contains L clusters [21]. Further more, each cluster is grouped by M adjacent subcarriers (OFDM tones). Therefore there are totally $K \times Q \times M$ subcarriers in the system.

B. *Frequency Fading Channels*

We consider UWB channels with frequency-selective fading. It's frequency-domain response is denoted as $H(f)$, which is the Fourier transform of its impulse response.

It's assumed that frequency response remains the same within a subcarrier for one data block. So the frequency response of the ith tone in the lth cluster can be described as $H(f_{il})$. Hence we express channel's information by a power attenuation factor D_{il}, which is defined as $D_{il} = |H(f_{il})|^2$. The factor D_{il} is a piecewise approximation of the channel transfer function. Then the received signal to noise ration (SNR) can be described as $\frac{D_{il}p_l}{N_0 B_{sub}}$, where p_l is the transmitted power in the lth cluster, $N_0 B_{sub}$ is the additive noise power within subcarrier bandwidth B_{sub} at a half side power spectral density $\frac{N_0}{2}$.

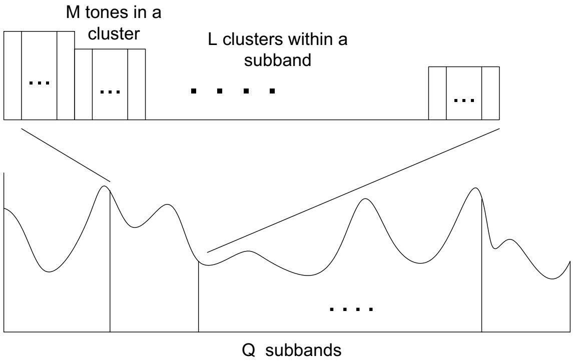

Fig. 1. A clustered multi-band OFDM scheme.

III. PROPOSED POWER ALLOCATION

A. *Problem Description*

It's assumed that channel state information (CSI) is available at the transmitters. Thus they allocate powers to different clusters according to CSI.

In order to improve throughput with an acceptable bit error rate (BER) guarantee, variable data rates can be sent according to subcarriers' channel conditions using adaptive modulation [21]. Hence tones with better conditions are assigned higher data rate and correspondingly more power to achieve larger throughput. It has been assumed that channel gain within a subcarrier is flat although it is variable within a cluster. Therefore within a tone the channel can be regarded as Guassian, and the achievable throughput per Hertz at the ith subcarrier of the lth cluster is bounded by [12]

$$c_{il} = \log_2(1 + SNR_{il}) = \log_2(1 + \frac{D_{il}p_l}{N_0 B_{sub}}).$$

Define $\gamma_{il} = \frac{D_{il}}{N_0 B_{sub}}$ to indicate the channel condition. Then it is simplified as

$$c_{il} = \log_2(1 + \gamma_{il}p_l),$$

where p_l is the allocated transmit power. Hence the throughput of the lth cluster per Hertz is

$$\overline{c_l} = \frac{1}{B_{clus}} \sum_{i=1}^{M} B_{sub} \log_2(1 + \gamma_{il}p_l) \tag{1}$$

where B_{clus} is the bandwidth of each cluster, and is related to B_{sub} by $B_{clus} = MB_{sub}$. Thus (1) becomes

$$\overline{c_l} = \frac{1}{M} \sum_{i=1}^{M} \log_2(1 + \gamma_{il}p_l). \tag{2}$$

As described in [3], each time only one subband is accessed and the transmitted signals hop among the Q subbands according to hopping codes. So in the proposed power allocation algorithm, each time $L \times M$ subcarriers within the accessed subband is considered.

The basic idea of our algorithm is to maximize the total throughput over the current subband with a total power constraint. Power is allocated in unit of cluster instead of subcarrier, which is different from the standard water-filling algorithm. As described in the previous section, the throughput of the lth cluster is given by (2). Because of L clusters, the following throughput of the entire system

$$\overline{c} = \frac{1}{LM} \sum_{l=1}^{L} \sum_{i=1}^{M} \log_2(1 + \gamma_{il} p_l)$$

can be maximized. Imposing a constraint on the total power P, considering polarity of each power and dropping a scalar, the optimization problem can then be described as

$$\max \sum_{l=1}^{L} \sum_{i=1}^{M} \log_2(1 + \gamma_{il} p_l)$$

subject to

$$p_l \geq 0,$$

$$\sum_{l=1}^{L} \sum_{i=1}^{M} p_l = P.$$

It is observed that the objective function is highly nonlinear. However, solution can be obtained by borrowing ideas from [22].

B. Solutions

To solve the optimization problem, it is transformed into a standard convex optimization problem

$$\min(-\sum_{l=1}^{L} \sum_{i=1}^{M} \log_2(1 + \gamma_{il} p_l)),$$

subject to

$$-p_l \leq 0,$$

$$\sum_{l=1}^{L} p_l = \frac{P}{M} \triangleq \overline{P}. \tag{3}$$

Introducing Lagrange multipliers λ_l for inequality constraints $-p_l \leq 0$, and a multiplier v for the equality constraint $\sum_{l=1}^{L} p_l = \overline{P}$, we obtain the Karush-Kuhn-Tucker (KKT in brief) conditions, whose solutions are those of the above optimization problem [22],

$$-p_l \leq 0, \tag{4}$$

$$\sum_{l=1}^{L} p_l = \overline{P}, \tag{5}$$

$$\lambda_l \geq 0, \tag{6}$$

$$\lambda_l p_l = 0, \tag{7}$$

$$-\sum_{i=1}^{M} \frac{\gamma_{il}}{1 + \gamma_{il} p_l} - \lambda_l + v = 0. \tag{8}$$

One can see from Eq. (8) that

$$\lambda_l = v - \sum_{i=1}^{M} \frac{1}{\alpha_{il} + p_l} \tag{9}$$

where

$$\alpha_{il} = \frac{1}{\gamma_{il}}.$$

From Eq. (6) and Eq. (9), one can achieve

$$v \geq \sum_{i=1}^{M} \frac{1}{\alpha_{il} + p_l}. \tag{10}$$

Also as shown in Eq. (7),

$$\begin{aligned} \lambda_l p_l &= p_l(v - \sum_{i=1}^{M} \frac{1}{\alpha_{il} + p_l}) \\ &= 0. \end{aligned} \tag{11}$$

Hence in order to satisfy Eq. (3), we require

$$\begin{aligned} p_l > 0 \ \text{ and } \ \sum_{i=1}^{M} \frac{1}{\alpha_{il} + p_l} = v, \ \text{ if } \ v < \sum_{i=1}^{M} \frac{1}{\alpha_{il}} \\ p_l = 0, \ \text{ if } \ v \geq \sum_{i=1}^{M} \frac{1}{\alpha_{il}}. \end{aligned} \tag{12}$$

The proof for Eq. (12) is provided as follows.

Proof: Under the condition that $v < \sum_{i=1}^{M} \frac{1}{\alpha_{il}}$, Eq. (10) can hold only if

$$p_l > 0,$$

which by Eq. (11) implies that

$$\sum_{i=1}^{M} \frac{1}{\alpha_{il} + p_l} = v. \tag{13}$$

If $v \geq \sum_{i=1}^{M} \frac{1}{\alpha_{il}}$, assume that $p_l \neq 0$, which implies that

$$p_l > 0.$$

Then

$$v \geq \sum_{i=1}^{M} \frac{1}{\alpha_{il}} > \sum_{i=1}^{M} \frac{1}{\alpha_{il} + p_l}.$$

From Eq. (11), one can conclude that $p_l = 0$. It's a contradiction to our assumption. So

$$p_l = 0 \ \text{ if } \ v \geq \sum_{i=1}^{M} \frac{1}{\alpha_{il}}. \tag{14}$$

From Eq. (13) and Eq. (14), one can conclude the proof. □

Considering (3), the solution can be rewritten compactly as

$$\begin{cases} p_l > 0, \ \sum_{i=1}^{M} \frac{1}{\alpha_{il} + p_l} = v & (\sum_{i=1}^{M} \frac{1}{\alpha_{il}} > v) \\ p_l = 0 & (\sum_{i=1}^{M} \frac{1}{\alpha_{il}} \leq v) \end{cases}$$

where v is a scalar that satisfies

$$\sum_{l=1}^{L} p_l = \overline{P}.$$

This algorithm can be implemented as follows.

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1) Set a small positive termination threshold $p_{thr}$ and step size $\xi$, initialize $v$ and $p_{total}$ to be zero.
2) While $|p_{total} - \overline{P}| > p_{thr}$, do

   for $l = 1 : L$
   {
   if $\sum_{i=1}^{M} \frac{1}{\alpha_{il}} \leq v$, $p_l = 0$;
   else
   find $p_l$ that satisfies $\sum_{i=1}^{M} \frac{1}{\alpha_{il}+p_l} = v$ by following steps:
      a) set a small positive termination threshold $v_{thr}$ and step size $\mu$ ;
      b) initialize $p_l = 0$;
      c) while $|v - \sum_{i=1}^{M} \frac{1}{\alpha_{il}+p_l}| > v_{thr}$, do
         find derivative $\delta$ of $(v - \sum_{i=1}^{M} \frac{1}{\alpha_{il}+p_l})^2$ with respect to $p_l$
            $\delta = \sum_{i=1}^{M} \frac{1}{(\alpha_{il}+p_l)^2}(v - \sum_{i=1}^{M} \frac{1}{\alpha_{il}+p_l})$,
         update $p_l$
            $p_l = p_l - \mu\delta$.
   }
   compute $p_{total} = \sum_{l=1}^{L} p_l$;
   update $v$ as
      $\frac{1}{v} = \frac{1}{v} + \xi(\overline{P} - p_{total})$.
3) Output all $p_l$'s.
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IV. NUMERICAL RESULTS

In this section, the proposed algorithm is applied in a clustered OFDM UWB system. Results are obtained based on a $1.8GHz$ channel model [23], located from $3.1GHz$ to $4.9GHz$. According to [3], the bandwidth is divided into three subbands, each with $528MHz$ corresponding to 128 subcarriers. One subband is accessed each time and a total power of $128mW$ is distributed through each subband.

A result of power allocation is shown in Fig. 2, where the x-axis is the index of the subcarriers and y-axis represents the power assigned to each subcarrier. The dashed line shows the result applying water-filling algorithm and the solid line represents the power assignment applying our algorithm. They are achieved in a channel whose SNR is $9dB$ and cluster size is 32 (i.e. a cluster has 32 subcarriers). SNR of the system is described as $\frac{P}{N_0 B_{total}}$, where B_{total} is the system bandwidth (i.e. $1.8GHz$). It is observed that the two algorithms yield similar power distribution over frequency. For those frequencies that are assigned more power in water-filling than other frequencies, the proposed algorithm also assigns more. On the other hand, those are assigned less power in water-filling also gain less power in the proposed algorithm.

The following part compares three power allocation methods: water-filling, algorithm by Zhang and Li [21] and the proposed algorithm. Fig. 3 shows the average throughput (bits/sec/Hz) from 30 independent channel realizations achieved by each of the three methods, where SNR ranges from $0dB$ to $10dB$ and cluster size M is 8. One can see that water-filling provides the largest throughput as expected and the method by Zhang and Li always provides the worst performance. The proposed algorithm exhibits performance close to water-filling. Especially when SNR increases, difference decreases. Fig. 4 represents the normalized throughput performance loss compared with water-filling method, which is defined as

$$\frac{\text{throughput of water\_filling} \; - \; \text{achieved throughput}}{\text{throughput of water\_filling}}.$$

In this figure, SNR is $8dB$ and cluster size ranges from 32 to 2. The loss of the proposed algorithm is from 0.4% to 5%, while the algorithm by Zhang and Li always has a performance loss above 10%. The proposed method always performs better. The loss of Zhang and Li's method becomes smaller when cluster size becomes larger. This is because when only one cluster is accessed each time, the larger the cluster size, the more bandwidth is considered in power allocation which brings better performance. It can also be concluded that our algorithm shows decreased performance loss when M decreases but requires increased complexity. So when selecting the cluster size, there should be a tradeoff between complexity and throughput.

V. CONCLUSION

In this paper, we have presented a power allocation algorithm for clustered multiband OFDM UWB networks. System throughput is maximized with respect to cluster powers under a total power constraint. Compared with a standard water-filling scheme, it has low complexity but close performance. It outperforms an existing power allocation method that selects only one best cluster each time.

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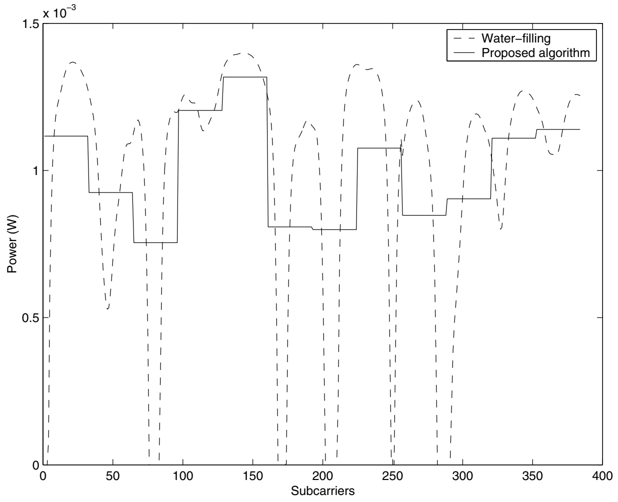

Fig. 2. Allocated power distribution.

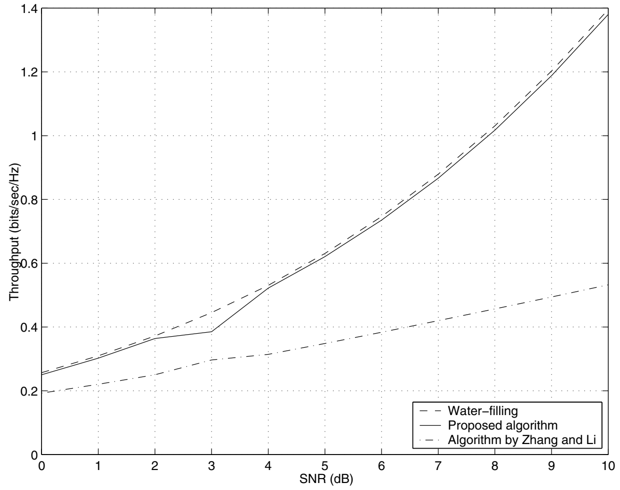

Fig. 3. Throughput of three algorithms: water-filling, algorithm in [21] and the proposed algorithm.

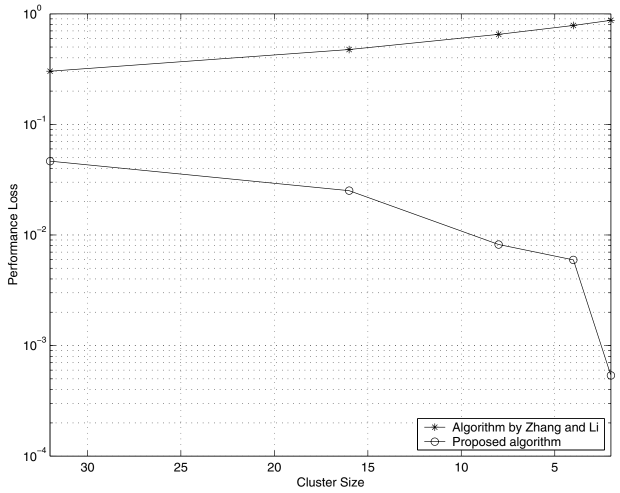

Fig. 4. Performance loss between water-filling and proposed algorithm, and loss between water-filling and algorithm by Zhang and Li.