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The Signaling Overhead in Dynamic OFDMA Systems: Reduction by Exploiting Frequency Correlation

James Gross, Pablo Alvarez, Adam Wolisz
TU Berlin
Einsteinufer 25, 10587 Berlin, Germany
{gross|wolisz}@tkn.tu-berlin.de

Abstract—Dynamic OFDMA systems provide a significant performance gain compared to static OFDM approaches. In reality this gain is reduced by an overhead due to signaling. Previous work has shown that this loss is particularly high if the number of sub-carriers is large. In this paper we present two approaches to reduce this overhead by exploiting the correlation in frequency. These two schemes are shown to provide a significant reduction of the signaling overhead.¹

I. INTRODUCTION

Dynamic Orthogonal Frequency Division Multiple Access (OFDMA) systems have promising performance characteristics for multi-user communication scenarios. Consider for example the down-link of a wireless cell employing Orthogonal Frequency Division Multiplexing (OFDM) as transmission scheme. As terminals roam through the cell, there is at any point in time a high frequency and spatial diversity of the sub-carrier gains. Hence, a sub-carrier with a low gain for some terminal can have quite a high gain for a different one. This diversity can be exploited by dynamic OFDMA systems: The access point assigns each terminal a set of disjunctive sub-carriers, based on channel state information of each sub-carrier for each terminal. These assignments have to be regenerated with a frequency in accordance with the coherence of the channel. Many assignment algorithms for such systems have been proposed, for example [1–3]. These algorithms have been shown to provide superior performance compared to static approaches.

This potential performance improvement comes at some cost - the *signaling overhead* - which is due to the fact that after computation only the access point knows the specific sub-carrier assignments (usually consisting of the information which terminal has received which sub-carrier and which modulation type). However, the terminals have to be informed of the assignments by signaling, after completing the computation but before utilizing the new assignments. Hence, there is some cost associated with dynamic OFDMA approaches. It has been shown that the difference between the theoretical performance due to dynamic OFDMA and the realistically

achievable performance is large [4], especially if the bandwidth is split into many sub-carriers or if there are many terminals present in the cell. Hence, schemes which can reduce the signaling impact are of interest. In [5] we have considered such a scheme which utilizes the time correlation of the sub-carrier gains. In this paper we are pursuing an alternative approach, considering the correlation of sub-carrier gains in frequency domain. The general line of argumentation is this: If the correlation of the sub-carrier gains is large (due to a high number of sub-carriers or a low delay spread, for example), the generated assignments also tend to be correlated in frequency. Then, this correlation can be exploited either by compression schemes (which is straightforward) or by having the assignment policy favor *bundle* assignments (the assignment of multiple adjacent sub-carriers to a single terminal). It turns out that exploiting the correlation in frequency can indeed reduce the cost due to signaling significantly, and outperforms the previously suggested approach.

The remaining paper is structured as follows: In Section II we present the underlying system model. Section III discusses then the two approaches considered. The two schemes are compared regarding their performance in Section IV before we conclude the paper in Section V.

II. SYSTEM MODEL

In this section we present our modeling approach. Note that it is in accordance with the model presented in [5].

A. General Model

We consider the down-link of a wireless system. The access point serves J terminals distributed over the area of a cell. Time is divided into frames of duration T_f . Each frame is split into a down-link and an up-link phase. We only focus on the down-link in the following. The given system bandwidth B is split into N sub-carriers. Per down-link phase S OFDM symbols are transmitted. We assume the transmit power to be evenly spread on the sub-carriers (thus, no dynamic power adaption is considered). The gain per sub-carrier and terminal, $h_{j,n}^{(t)}$, varies due to path loss, shadowing and fading. The perceived signal quality per sub-carrier, i.e. the SNR, varies from frame to frame while it is assumed to be constant during

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one frame. Per sub-carrier adaptive modulation is applied, a total of M modulation types are available. For the application of the adaptive modulation an upper error probability limits the SNR range any particular modulation type is applied to. Thus, given the SNR for a certain sub-carrier/terminal pair, the choice of modulation is well-defined (denote by $b_{j,n}^{(t)}$ the number of bits the chosen modulation type could convey per symbol on sub-carrier n to terminal j). OFDMA is applied during the down-link phase. Prior to each down-link phase, the access point generates new assignments based on the knowledge of the sub-carrier states. We assume perfect channel knowledge at the access point. Binary variables represent the assignment decisions, i.e. $x_{j,n}^{(t)} = 1$ if terminal j is assigned sub-carrier n for down-link phase t . Each sub-carrier can be assigned to at most one terminal at a time.

We assume that the access point has per terminal a large data file stored for transmission. Thus, for each frame each terminal has a large amount of data queued at the access point. Apart from the (effective) average throughput per terminal, we do not consider any other metrics related to the transmission of the data.

B. Dynamic OFDMA Approach

As objective function for the sub-carrier assignment we consider the maximization of throughput. However, a pure rate maximization leads to fairness problems (i.e. strongly different average throughput per terminal) in OFDMA based cells, due to the individual path loss coefficients per terminal. Hence, in the literature the notion of the *rate-adaptive* optimization approach has been discussed [3, 6]. In this approach the minimum rate per cell is maximized for each down-link phase. This basically solves the fairness problems but has been shown to be NP-hard [7]. Therefore, we consider an assignment approach where the *number* of sub-carriers assigned to each terminal is fixed to some value l_j . Based on these values the sum rate of the cell is maximized:

$$\begin{aligned} \max \quad & S \cdot \sum_{j,n} b_{j,n}^{(t)} \cdot x_{j,n}^{(t)} \\ \text{s.t.} \quad & \sum_j x_{j,n}^{(t)} \leq 1 \quad \forall n \\ & \sum_n x_{j,n}^{(t)} \leq l_j \quad \forall j \end{aligned} \quad (1)$$

While this approach does not achieve total fairness between different terminals, the approach itself can be solved in polynomial time as this reduces to a bipartite weighted matching problem [8]. Hence, it is a realistic approach for application.

C. Signaling Overhead

As the dynamic sub-carrier assignments are generated at the access point, the terminals do not know about their assignments as such. Hence, prior to each down-link phase, the *signaling information* has to be transmitted. We assume that a separate signaling phase is introduced prior to the down-link phase. During this signaling phase, the signaling information is transmitted on all N sub-carriers using a predefined modulation/coding

Fig. 1. FSSF model: Representation of assignment information for one down-link phase.

combination (which can transmit b_{sig} bits per symbol). Denote the number of OFDM symbols required for the transmission of the signaling information by ς . We assume that for the signaling phase and the down-link phase a total of S symbols are available. Thus, the less time is consumed for the transmission of the signaling information, the more time is available for the payload transmission itself. The specific value of ς depends on the binary representation of the assignments. In general, the basic information unit describing an assignment consists of the triple: $\langle \text{Sub-carrier ID, Terminal Address, Modulation ID} \rangle$. We refer to such a basic unit as *signaling word*. In [4] a simple signaling scheme was proposed, referred to as fixed size signaling field model (FSSF - cf. Figure II-C). In this model all assignments are announced during each signaling phase. Thus, the position of the tuple $\langle \text{Terminal Address, Modulation ID} \rangle$ in the bit stream (of the signaling phase) indicates the sub-carrier ID the tuple relates to. Note that we require $\lceil \log_2(J) \rceil + \lceil \log_2(M) \rceil$ bits for a signaling word due to FSSF model.

III. REDUCTION OF SIGNALING OVERHEAD

It can be shown that the signaling overhead has a significant impact on the throughput of dynamic OFDMA systems [5] - a fact that is often neglected in studies regarding such approaches. Moreover, the signaling overhead is parameter-dependent. For example, as the number of sub-carriers increases the signaling overhead grows, leading to a decreasing *effective* throughput the more sub-carriers are employed (while keeping the overall bandwidth fixed). The same is true for the number of terminals as well as some other parameters.

However, the FSSF model is not very efficient. In principle, the signaling overhead can be reduced by exploiting correlation either in *time* and/or in *frequency*. Depending on a couple of system and environment parameters (like the center frequency, terminal velocity, delay spread, frame length, number of sub-carriers, system bandwidth), the sub-carrier gains are more or less correlated in time and frequency². Hence, sub-carrier assignments can also happen to be more or less correlated in time and frequency. In fact, the assignment algorithm solving problem (1) can be driven to make assignments more correlated. Then, a more efficient binary representation than the FSSF model can reduce the signaling overhead. In [5] we have investigated one such scheme exploiting the correlation in *time*.

²For example, the correlation in frequency of a certain cell depends on the signals delay spread of the area covered by that cell which can be measured during cell installation.

Fig. 2. Representation of assignment information for one down-link phase in order to exploit the correlation in frequency.

We found that the overhead due to the FSSF model can be reduced at the expense of additional computational power. In this paper we investigate the reduction potential if the frequency correlation is exploited instead. This is substantially different from exploiting the correlation in time (leading to different binary representations and different optimization problems) and leads to new insights regarding dynamic OFDMA systems. In particular, we study two approaches. The first one is an optimization problem, building on the basic approach (1). The second approach is inspired by a paper on reduction of the *bit loading* signaling overhead in OFDM point-to-point communications: In [9] it is proposed to reduce the overhead by compression. Thus, we choose compression as second scheme to be investigated. In Section IV both approaches are benchmarked against the best time-correlation reduction scheme from [5].

A. Optimization Approach

Initially, consider a representation of the signaling information such that multiple assignments of adjacent sub-carriers to the *same* terminal are represented by a single signaling word (cf. Figure 2). We refer to such a set of sub-carrier assignments as *bundle*. Formally, we define a bundle as a set of adjacent sub-carriers which are all utilized *with the same modulation type and assigned to the same terminal*. Given the position of a bundle assignment and all bundle sizes of previous ones, the sub-carrier IDs of that bundle can be determined. The number of bits required for one signaling word is higher than in the case of the FSSF model and is given by:

$$C_{\text{sig}} = \lceil \log_2(J) \rceil + \lceil \log_2(M) \rceil + \lceil \log_2(A) \rceil \quad (2)$$

Here, A denotes the largest number of sub-carriers which can be combined to one bundle.

This new representation could be applied to the assignments resulting from optimization problem (1). If sub-carrier assignments tend to be correlated in frequency, this new representation pays off. However, it is also possible to modify the assignment problem in (1) to optimally “produce” bundle assignments.

Recall that the total down-link phase contains S symbols for data transmission. The number of symbols required for conveying the signaling information is denoted by ς . Clearly, ς depends on the number of bundles formed. If only a few large bundles are assigned, ς is lower than if a lot of small bundles are assigned. However, the effective throughput achieved per down-link phase depends on the sum rate per OFDM symbol

Fig. 3. The difference between the bipartite matching graph of opt. problem (1) and the matching graph in case of bundles (for 3 terminals, 3 sub-carriers and a setting of $A = 2$, note that only the bundle weights for terminal 1 are shown). In this example bundles 1, 2, 3 are equal to a single sub-carrier assignment, bundle 4 (the fourth bundle in the figure above) consists of sub-carrier 1 and 2 while bundle 5 consists of sub-carrier 2 and 3. For all sub-carriers of a bundle the modulation type is set to the smallest one of all sub-carriers in this bundle. Note that in the figure above the total bundle weight is shown (not the weight of the modulation type).

during the payload transmission (as given by $\sum_{j,n} b_{j,n}^{(t)} \cdot x_{j,n}^{(t)}$) as well as on the total number of symbols available for payload transmission, given by $S - \varsigma$.

For the further discussion let us assume that ς is fixed to some value. Then there is an upper limit to the number of bundles that can be signaled, denoted by $\bar{\varsigma}$. Now the problem arises to find the maximum sum rate with respect to $\bar{\varsigma}$. Notice that this is not a bipartite weighted matching problem any more. Instead, the weighted bipartite graph is extended by additional nodes which represent the bundles, i.e. the $N + 1$ node represents the bundle of sub-carrier 1 and sub-carrier 2 (cf. Figure 3). As the bundles are defined to have the same modulation type, the weight of each bundle is set to the smallest modulation type of all corresponding sub-carriers (multiplied by the number of sub-carriers contained in the bundle). Hence, based on the bit matrix $\mathbf{B}^{(t)}$ a new bit matrix $\bar{\mathbf{B}}^{(t)}$ is built, containing the “bit worth” $b_{j,g}^{(t)}$ of each bundle g regarding each terminal j . The number of all bundles G depends on the maximum size of sub-carriers A a bundle can combine. In

general, the number of bundles computes to

$$G = \sum_{i=0}^{A-1} (N - i) \quad . \quad (3)$$

The assignment matrix $\mathbf{X}^{(t)}$ is changed accordingly, holding binary entries on the assignment decision $x_{j,g}^{(t)}$ of bundle g to terminal j at time t . Thus, the total number of assigned bundles computes to $\sum_{j,g} x_{j,g}^{(t)}$. Recall that so far we assumed a limit on the total number of bundle assignments, i.e. we consider the constraint $\sum_{j,g} x_{j,g}^{(t)} \leq \mathfrak{x}$. We are looking for a maximum sum rate bundle assignment with respect to $\mathfrak{x}$ and the constraints as given in the original bipartite weighted matching problem (1) (which are: a sub-carrier can only be assigned to one terminal and each terminal has to receive his share of l_j sub-carriers). In order to preserve the allocation constraints of problem (1), an “inclusion” matrix has to be constructed with binary entries $i_{n,g}^{(t)}$, indicating if sub-carrier n is an element of bundle g or not. Then the above described maximum weight bundle assignment problem is given by Equation:

$$\begin{aligned} \max \quad & \sum_{j,g} \left(b_{j,g}^{(t)} \cdot x_{j,g}^{(t)} \right) \\ \text{s.t.} \quad & \sum_{j,g} i_{n,g}^{(t)} \cdot x_{j,g}^{(t)} \leq 1 \quad \forall n \\ & \sum_{n,g} i_{n,g}^{(t)} \cdot x_{j,g}^{(t)} \leq l_j \quad \forall j \\ & \mathfrak{x} \geq \sum_{j,g} x_{j,g}^{(t)} \quad . \end{aligned} \quad (4)$$

The solution of this problem is at the core of the optimization approach discussed here. However, a further problem arises from the fact that $\mathfrak{x}$, i.e. ς , is not known. Instead, given the number of bits required to represent a bundle assignment from Equation 2, the number of required signaling symbols is obtained by Equation (5) (if the bundle assignments $x_{j,g}^{(t)}$ are known).

$$\varsigma = \left\lceil \frac{\sum_{j,g} C_{\text{sig}} \cdot x_{j,g}^{(t)}}{N \cdot b_{\text{sig}}} \right\rceil \quad (5)$$

Now we can extend problem (4) to the general case where both ς and the assignments $x_{j,g}^{(t)}$ are unknown. Finally, the overall optimization problem (maximizing the net throughput per down-link phase) to be solved is given in (6).

$$\begin{aligned} \max \quad & \left(S - \left\lceil \frac{\sum_{j,g} C_{\text{sig}} \cdot x_{j,g}^{(t)}}{N \cdot b_{\text{sig}}} \right\rceil \right) \cdot \sum_{j,g} \left(b_{j,g}^{(t)} \cdot x_{j,g}^{(t)} \right) \\ \text{s.t.} \quad & \sum_{j,g} i_{n,g}^{(t)} \cdot x_{j,g}^{(t)} \leq 1 \quad \forall n \\ & \sum_{n,g} i_{n,g}^{(t)} \cdot x_{j,g}^{(t)} \leq l_j \quad \forall j \quad . \end{aligned} \quad (6)$$

The optimization problem (6) is a quadratic programming problem with integer constraints. The quadratic nature of the problem can be resolved by sophisticated enumeration

strategies, as discussed in [5]. This ends up with solving a sequence of problems as given in Equation (4). However, problem (4) describes a new kind of constrained weighted matching problem for which the complexity is not known so far. Apart from the theoretical complexity, we have observed that the practical run times depend strongly on the setting of A (which has an impact on the number of columns of the corresponding integer program). We suggest to set A according to the coherence bandwidth W_c [10].

B. Compression Approach

As second scheme we propose that the output of the assignments from the basic dynamic OFDMA approach (1) is compressed using an algorithm introduced by Bentley, Sleator, Tarjan and Wei [11] – hence the name BSTW. The BSTW scheme has the benefit of taking advantage of *locality of reference*, which is the tendency for a certain source message to occur frequently for a short period of time and then fall into long periods of disuse. This is exactly the mechanism that can exploit the correlation of assignments in frequency. Trains of the same FSSF signaling words for adjacent sub-carriers can be compressed.

BSTW works as follows: Transmitter and receiver maintain identical code representations of the signaling words. The coding list is initially empty. When an assignment i is transmitted, if i is on the transmitters list, its current position in the list is transmitted. Then the list is updated by moving i to position 1 and shifting each of the other encodings down one position. The receiver similarly alters the encoding list. If i is being transmitted for the first time, then $k + 1$ is the “position” transmitted, where k is the number of distinct words transmitted so far. Some representation of the assignment itself must then be transmitted as well, but just for this first time (for example, the FSSF representation). Then i is moved to position 1 by both transmitter and receiver subsequent to its transmission.

BSTW can be easily implemented and requires only a few computational resources. However, this compression approach has also an important disadvantage. If an undetected bit error occurs, transmitter and receiver will rapidly loose synchronization, since the receiver will update the assignment list wrongly and both instances will maintain different encoding list from then on. This might make it necessary to use stronger error correction techniques in addition to compression, since correctly decoding the signaling information is crucial for the system’s performance. However, errors in the compressed information have not been considered further. A further disadvantage is that computational power has to be present at the transmitter *as well as* at the receiver to employ this scheme. This is a significant difference to the above presented optimization scheme.

IV. PERFORMANCE EVALUATION

We have evaluated the performance of the two different frequency correlation approaches (optimization versus compression) by means of simulation. As metric we have chosen the effective throughput, i.e. the average throughput per terminal for payload transmission *after* taking into account the signaling

overhead - assuming each terminal to down-load some large data file from the access point, for example.

The two schemes presented in Section III-A and III-B are benchmarked against three comparison schemes. Firstly, we consider the performance obtained if not taking the signaling overhead into account. Thus, this refers to the throughput given by solving the basic dynamic OFDMA problem (1). Obviously, this serves as upper bound. The second comparison scheme is the effective throughput obtained from solving problem (1) but accounting for the signaling impact with respect to the FSSF model. Note that the FSSF model provides no means to exploit any correlation of the assignments. Hence, this scheme serves as lower bound on the effective throughput. As third comparison scheme we chose the best results from exploiting the *correlation in time* of assignments between consecutive frames, as presented in [5].

The following basic simulation scenario is chosen: The cell radius is $r_{\text{cell}} = 100$ m and the center frequency is set to $f_c = 5.2$ GHz. The maximum transmit power equals $P_{\text{max}} = 10$ mW. The guard interval length is set to $T_g = 0.8 \mu\text{s}$ (in correspondence to IEEE 802.11a [12]). $J = 8$ terminals are assumed to be located in the cell. Time is divided into frames of length $T_f = 2$ ms, equally split into down-link and up-link phase.

The sub-carrier gains $(h_{j,n}^{(t)} = h_{\text{pl}}^{(t)} \cdot h_{\text{sh}}^{(t)} \cdot h_{\text{fad}}^{(t)})$ are generated based on the three components path loss, shadowing and fading. For the path loss, a standard model $h_{\text{pl}}^{(t)} = K \cdot \frac{1}{d^\alpha}$ is assumed [10]. As parameters, we use $K = 46.7$ dB and $\alpha = 2.4$, corresponding to a large open space propagation environment. For the shadowing $(h_{\text{sh}}^{(t)})$, we assume independent stochastic samples from a log-normal distribution, characterized by a zero mean and a variance of $\sigma_{\text{sh}}^2 = 5.8$ dB. The samples are regenerated every second. While the path loss and shadowing affects all sub-carriers of a terminal alike, each sub-carrier experiences its own fading component. Each sample $h_{\text{fad}}^{(t)}$ of the fading process is assumed to be Rayleigh-distributed. The frequency and time correlation of $h_{\text{fad}}^{(t)}$ are characterized by a Jakes-like power spectrum and an exponential power delay profile. The Jakes-like power spectrum is parameterized by the maximum speed within the propagation environment (set to $v_{\text{max}} = 1$ m/s) and the center frequency f_c . The exponential power delay profile is characterized by the delay spread $\Delta\sigma$. The noise power σ^2 is computed at an average temperature of 20°C over the bandwidth of a sub-carrier.

For the adaptive modulation scheme, a target symbol error probability of $p_{\text{max}} = 10^{-2}$ is chosen for the payload transmission. A total of $M = 4$ modulation types are available, namely BPSK, QPSK, 16-QAM and 64-QAM. Thus, BPSK is applied in the SNR range between 4 and 9 dB, QPSK is applied between 9 and 16 dB, 16-QAM is applied between 16 and 22 dB, and 64-QAM above a SNR value of 22 dB. For the signaling phase, we use BPSK in combination with a rate $1/2$ convolutional coder (assuming soft decision), resulting in $b_{\text{sig}} = 0.5$. This results in a very low bit error probability for the signaling part.

Fig. 4. Average net throughput per terminal for an increasing number of sub-carriers for the two introduced schemes exploiting the correlation in frequency (BSTW and Opt. Model in Freq.) and the three comparison schemes (No Sig. Cost, FSSF, Opt. Model in Time).

We present here results for two different cases. Consider initially Figure 4, where the number of sub-carriers is varied between $N = 64$ and $N = 512$. In this case the delay spread is set to $\Delta\sigma = 0.15 \mu\text{s}$. As the number of sub-carriers increases, the theoretical throughput increases. This is due to the fact that the cyclic prefix is kept fix and hence, more and more time is used for payload data transmission as the OFDM symbol duration increases with an increasing number of sub-carriers. However, *all* schemes including the signaling overhead first increase but decrease after some peak value. Compared to the performance of the FSSF model the two schemes which exploit the correlation in frequency achieve a large performance gain. In fact, the difference between the theoretical throughput limit and the optimization approach is only 4% for $N = 256$. The BSTW approach performs slightly lower (compared to the optimization approach) with a 8% difference to the upper limit. Compared to the best scheme exploiting the correlation in time, both frequency approaches provide a substantial improvement. However, notice also that the performance improvement is much larger for large settings of the number of sub-carriers (especially in the case of $N = 512$). This is due to the high correlation in frequency if the bandwidth is split into many sub-carriers. This dependency on the correlation in frequency is further investigated by considering the variation of the delay spread in Figure 5. In this case the number of sub-carriers was set to $N = 128$ and the delay spread varies between $\Delta\sigma = 0.1 \mu\text{s}$ and $\Delta\sigma = 0.5 \mu\text{s}$ (note that the cyclic prefix was fixed at $T_g = 0.8 \mu\text{s}$). As the delay spread increases, an increase of the throughput can be observed in general, stemming from a larger frequency diversity. However, as the delay spread increases, precisely this effect reduces the efficiency of the frequency schemes: As the correlation of adjacent sub-carriers decreases, the reduction of the signaling overhead becomes lower and lower (leading to a larger gap between the theoretical throughput limit and the net throughput of the frequency

Fig. 5. Average net throughput per terminal for an increasing delay spread for the two introduced schemes exploiting the correlation in frequency (BSTW and Opt. Model in Freq.) and the three comparison schemes (No Sig. Cost, FSSF, Opt. Model in Time).

schemes). At the largest delay spread point, all three reduction schemes provide the same net throughput. However, for a rather low delay spread, the optimization approach provides almost the throughput of the theoretical limit while the BSTW compression approach has a significantly lower net throughput.

V. CONCLUSIONS

In this paper we consider two schemes which exploit the correlation in frequency in order to decrease the signaling overhead in dynamic OFDMA systems. While the first approach is a “traditional” one based on a compression algorithm, the second scheme is more sophisticated as it optimizes the assignments with respect to the net throughput.

We show that both schemes can reduce the signaling overhead significantly compared to state-of-the art approaches. Compared to a static signaling scheme, the net throughput is improved by 20% and more. Among the two frequency reduction schemes complexity seems to favor the compression approach as the theoretical complexity of the optimization approach is not known currently. However, the optimization approach outperforms the compression approach slightly. This small performance difference could become quite important as the error coding requirements for the signaling information can be much higher in general. Compared to exploiting the correlation in time, the frequency approach provides a significantly better performance in most cases. As the correlation in frequency is usually high in OFDM systems (as this ensures frequency flat fading per sub-carrier) we conclude that exploiting the correlation in frequency is a better solution for overhead reduction in dynamic OFDMA systems.

As future work we consider two issues: First of all, the signaling overhead could be further decreased by an approach combining the correlation in time as well as the correlation in frequency. In addition, we are considering polynomial time

algorithms for the assignment problem (4) to clarify the complexity issues.

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