Joint Network Coding and Subcarrier Assignment in OFDMA-Based Wireless Networks

Xinyu Zhang, Baochun Li
Department of Electrical and Computer Engineering
University of Toronto
Email: {xzhang, bli}@eecg.toronto.edu

Abstract—**Orthogonal Frequency Division Multiple Access (OFDMA) has been integrated into emerging broadband wireless access technologies such as 802.16 wirelessMAN. Due to the diversity of channel gains among the downlink subscribers, it is known that dynamic allocation of subcarriers can significantly improve the overall performance of OFDMA systems, in terms of power efficiency and link throughput. A large body of work has focused on the joint subcarrier assignment and resource (bit and power) allocation for the OFDMA downlink. In this paper, we adopt a cross layer approach towards a network coding aware subcarrier assignment algorithm for the uplink and downlink of OFDMA based wireless networks. We formulate the maximal rate assignment problem as a mixed integer linear program and derive a polynomial time heuristic to approximate the solution. With network coding, it becomes possible to assign the same subcarrier to different downlinks without causing any interference. Consequently, our coding-aware assignment scheme improves the bandwidth efficiency and increases the network layer throughput by a substantial margin. We show that the total network throughput resulting from the heuristic is comparable to the optimal solution, with slight compromise of fairness. In addition, the coding aware subcarrier assignment mechanism can be applied to other multichannel wireless systems as well.**

I. INTRODUCTION

As a key component of the state-of-the-art IEEE 802.16 standard [1], Orthogonal Frequency Division Multiple Access (OFDMA) promises to support broadband access in infrastructure based wireless networks. With OFDMA, the prescribed bandwidth is divided into multiple orthogonal frequency bands called *subcarriers*. Each subscriber station (SS) is allocated a number of subcarriers by the base station (BS). The throughput of a downlink or uplink is proportional to the number of subcarriers allocated to the corresponding SS, as well as the achievable rate of each subcarrier. In a frequency-selective multipath fading environment, different subcarriers have diverse channel gains for the same SS, and even the same subcarrier fades independently for different SSs. Such diversity has motivated the design of dynamic mechanisms in OFDMA based wireless networks. In particular, a large body of research work has focused on the downlink subcarrier assignment and resource (bit and power) allocation schemes, aiming at maximizing link rate or minimizing transmission power (see *e.g.*, [2]–[4]). However, most of the related work is confined to the dynamic mechanisms within the MAC and PHY layers.

In this paper, we propose a cross-layer subcarrier assignment scheme CADSA (**C**oding **A**ware **D**ynamic **S**ubcarrier **A**ssignment) that explores the advantages of network coding in OFDMA systems. We consider the network scenarios where

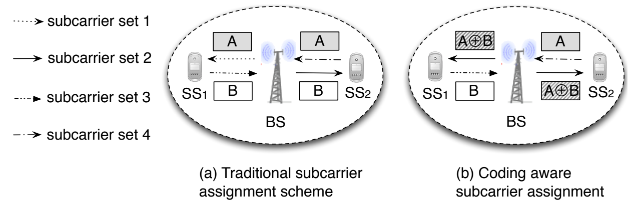

Fig. 1. The motivating scenario for coding aware subcarrier assignment in OFDMA wireless networks.

the BS serves as a relay station for multiple SSs, and both the uplink and downlink subcarriers are allocated by the BS via a centralized manner. As a preliminary evaluation, we study the simplest form of network coding, *i.e.*, coding over $GF(2)$ [5], [6], which allows the BS to XOR two incoming data frames heading towards different subscribers, based on *a priori* knowledge of whether they can be decoded. The BS broadcasts the XORed frames to two SSs through the same subcarriers, thereby saving the resource usage compared with traditional subcarrier assignment schemes. The subscribers can extract different information from the same XORed frame by XORing it with one that was previously sent to the BS. As an intuitive justification of the network coding benefits, consider the scenario in Fig. 1, where two SSs are exchanging information with each other via the base station. Traditional subcarrier assignment schemes would assign orthogonal sets of subcarriers to the two downlinks. When network coding is applied, however, the uplink frames can be XORed and routed to both downlink SSs through the same set of subcarriers, saving one set of subcarriers to serve for other links.

In an ideal case where each SS is interested in exchanging information with another one, and the subcarriers have uniform channel gains for all uplinks and downlinks, it is straightforward that to achieve the same network capacity, traditional subcarrier assignment schemes would require $\frac{1}{3}$ times more subcarriers than the coding aware scheme. In other words, network coding is able to boost the aggregate throughput by $\frac{1}{3}$. When the SSs experience diverse channel conditions, however, we need to balance a trade-off between diversity gain and the network coding advantage. For instance, when BS $\rightarrow$ SS$_1$ has much lower channel gain than BS $\rightarrow$ SS$_2$ (Fig. 1), sharing the same subcarriers may result in lower throughput than assigning them separately, since the throughput of both links is restricted by the rate of BS $\rightarrow$ SS$_1$.

To quantify the true benefits of network coding in practical OFDMA systems, we formulate an optimization problem that jointly accounts for network coding and subcarrier allocation. Since the problem is NP-hard, we design a polynomial time heuristic algorithm that can be applied to real OFDMA wireless networks such as 802.16. Our simulation experiments under realistic fading channel models demonstrate that the throughput performance of the algorithm is comparable to the optimal one, though with a slightly lower level of fairness. The performance gains of CADSA, in comparison with dynamic subcarrier allocation schemes without network coding, can be close to the $\frac{1}{3}$ bound in good channel conditions, and diminishes as the SSs experience diverse channel conditions. On the other hand, CADSA consistently achieves much higher throughput than the random assignment algorithm in current 802.16 standard. To the best of our knowledge, this is the first work that explores the benefits of network coding in emerging multichannel wireless technologies.

The remainder of this paper is organized as follows. In Sec. II, we present a literature review of existing work on network coding and dynamic assignment mechanisms in OFDMA systems. Sec. III describes the system models and formulates the throughput maximization problem. We then design a heuristic algorithm in Sec. IV, and subsequently evaluate its performance in Sec. V, in comparison with other related schemes. Finally, Sec. VI concludes the paper.

II. Related Work

Dynamic mechanisms for OFDMA systems were first introduced by Wong *et al.* [2]. They formulated the subcarrier assignment and power allocation problem as a mixed integer program, and derived a heuristic solution using Lagrange relaxation and LP-rounding method. Multiple subsequent work explored variants of the problem, focusing on different objectives (minimizing power subject to rate constraint or maximizing total downlink rate) and solutions with lower complexity (see [7] for a survey). In general, these algorithms involve two aspects: subcarrier assignment, which selects the set of subcarriers for each link; and resource allocation, which allocates power and bit to each subcarrier subject to the total power budget and rate requirement. Both aspects involves integer or nonlinear constraints and are hard to solve in general. Suboptimal solutions have been proposed that solve the two problems separately. For instance, [8] assumes equal power allocation for all subcarriers, and shows that the sum capacity is close to the optimum. [3] used a similar algorithm to assign subcarriers, and applied the water-filling approach to distribute power. As in other power allocation algorithms, the solution is based on a continuous relation between SNR and subcarrier rate, while only a stepwise function is applicable in real systems like 802.16. Most of the above work focused on the MAC and PHY issues in the downlink of single-cell OFDMA wireless networks.

Network coding has been a promising information theoretic approach to improve the performance of wireless networks. By allowing encoding operations at intermediate relays, it has been shown in [5], [6] that even simple XOR coding can considerably increase network throughput. Following such seminal work, a series of analysis and protocols have been explored (see *e.g.*, [9], [10]). However, most of the related work takes advantage of the interference reduction capabilities of network coding for CSMA based 802.11 wireless networks. We are not aware of any existing work on the benefits of network coding in state-of-the-art multi-channel networks like 802.16.

III. The Optimization Formulation

In this section, we introduce the models for CADSA in OFDMA wireless networks, and subsequently formulate the optimization problem based on these models.

A. System Models

We consider a cell-like *wireless switching network* [9], where the base station serves as an intermediate relay that switches data frames from one SS to another SS within the same cell. Unlike the single-channel model in [9], we assume the switching network is built atop OFDMA, thus subcarrier assignment becomes a critical problem. Such network scenarios can be seen in multihop OFDMA systems such as 802.16j and its extensions.

It is known that the fading processes of SSs located in different places are independent, even if they are using the same subcarrier [7]. The maximum achievable rate of each subcarrier is a stepwise function of the SNR, which depends on its fading profile (channel gain), as well as the amount of power allocated to it. It has been observed that allocating diverse power levels to subcarriers provides marginal performance improvement when compared with equal power allocation [8]. Therefore, in our formulation the downlink power budget is averaged over all available subcarriers. The per-subcarrier power on the uplink equals to that of the downlink. We further assume the system is based on FDD, *i.e.*, the uplink and downlink are assigned disjunctive set of subcarriers such that they can transmit at the same time.

Before each uplink/downlink phase (the period for one uplink/downlink frame), the BS must assign subcarriers for the next phase based on available channel state information, and transmit the results via the downlink. The uplink channel states are estimated by the built-in pilot carriers in OFDMA systems. For those subcarriers that are not directly used, the channel gain can be estimated using model based method [11]. The downlink channel gains are estimated by the corresponding SS and sent to the BS in the next phase. To ensure channel knowledge is not outdated, the channel state must remain stable over two phases, *i.e.*, the coherence time must be longer than the period of two frames. This is valid for low mobility scenarios with SSs that are static or moving at pedestrian speed. Note that the estimation of channel state and the transmission of the subcarrier assignment results introduce signaling overhead, which we discuss in Sec. V.

In general, the XOR network coding opportunities exist in two types of scenarios: the *information exchange paradigm* and the *opportunistic listening paradigm* [10]. In both paradigms, the encoding node is the shared relay (the BS) for different sessions (the traffic from one SS to another is called a *session*). An XOR encoding happens only if the BS estimates that the corresponding downlink SSs have all but one of the frames that are encoded, and the missing one is exactly what each SS is intended to obtain by decoding. In particular, for the former case, each SS decodes the encoded frame by XORing it with one that it previously sent and cached, which is best illustrated in Fig. 1. In the latter case, the encoded frame is XORed with frames that the SS overheard from neighboring SSs [6]. Since we assign orthogonal set of subcarriers to the uplink, the SSs no longer have overhearing capabilities. Therefore, we only need to account for the information exchange paradigm.

B. The Optimization Problem

The main objective of our formulation is to assign appropriate set of subcarriers to the uplink and downlink of each session, such that the total capacity (network layer throughput) of the switching network is maximized while no session is starved. Denote the throughput of session s as λ_s, then the objective function can be expressed as $\max\ \min_s \lambda_s$, or equivalently:

$$\max \qquad \lambda \tag{1}$$

$$\text{subject to:} \quad \lambda \leq \lambda_s \tag{2}$$

We proceed to introduce the corresponding constraints. First, the end-to-end throughput is bounded by the achievable rate on the uplink and downlink. Denote $R(c, n)$ as the rate of subcarrier c when it is assigned to node n, and x^u_{cs} as the 0-1 decision variable indicating whether subcarrier c is assigned to the uplink of session s. Let s_{src} denote the source node (*i.e.*, the uplink SS) of session s, then the uplink throughput constraint is:

$$\lambda_s \leq \sum_c R(c, s_{src}) \cdot x^u_{cs} \tag{3}$$

Similarly, we can derive the throughput constraint on the downlink. Denote b_{rs} as the throughput contributed by subcarriers transmitting XORed frames for session r and s; and u_s as the throughput of session s contributed by uncoded traffic. We dictate $r < s$ for b_{rs} so as to avoid repeated count. Consequently, we have:

$$\lambda_r \leq \sum_s b_{rs} + u_r, \text{ and } \lambda_s \leq \sum_r b_{rs} + u_s \tag{4}$$

Furthermore, if two downlinks share one subcarrier, then the subcarrier's rate must conform to the one with lower achievable rate, *i.e.*, the XORed traffic rate equals to the lower rate of the two encoded sessions. Denote s_{dst} as the destination node (*i.e.*, the downlink SS) of session s; and x^d_{cs} as the 0-1 variable indicating whether subcarrier c is assigned to session s as a downlink channel. Then,

$$b_{rs} = \sum_c \min(R(c, r_{dst}), R(c, s_{dst})) \cdot x^d_{cr} \cdot x^d_{cs}, \tag{5}$$

The multiplication of two variables x^d_{cr} and x^d_{cs} imposes a nonlinear constraint. To simplify the problem, we introduce an additional variable y^c_{rs} and linearize the constraint as follows. Let $y^c_{rs} \in \{0, 1\}$ and $y^c_{rs} = x^d_{cr} x^d_{cs}$, then the constraint (5) is equivalent to:

$$b_{rs} = \sum_c \min(R(c, r_{dst}), R(c, s_{dst})) \cdot y^c_{rs}, \tag{6}$$

$$y^c_{rs} \leq x^d_{cs} \tag{7}$$

$$y^c_{rs} \leq x^d_{cr} \tag{8}$$

In addition, the amount of uncoded downlink traffic can be obtained by subtracting the potential rate of codable subcarriers from the total rate of all subcarriers, *i.e.*,

$$u_r = \sum_c R(c, r_{dst}) x_{cr} - \sum_c \sum_s R(c, r_{dst}) y^c_{rs}, \text{ and:}$$

$$u_s = \sum_c R(c, s_{dst}) x_{cs} - \sum_c \sum_r R(c, s_{dst}) y^c_{rs} \tag{9}$$

Finally, except for those carrying XORed traffic, one subcarrier can only be allocated to at most one session. Therefore, we have the following constraint:

$$\sum_s x^u_{cs} + \sum_s x^d_{cs} - \sum_{(r,s)} y^c_{rs} \leq 1 \tag{10}$$

Consequently, the CADSA optimization becomes a mixed-integer linear program, with the objective (1), subject to constraints (2), (3), (4), (6), (7), (8), (9) and (10).

As a benchmark comparison, we also study a dynamic subcarrier allocation scheme without network coding (referred to as NO-CODE), which extends existing optimization based OFDMA downlink-only assignment algorithms [7]. The optimal solution is derived from the following optimization framework:

$$\max \qquad \lambda \tag{11}$$

$$\text{subject to:} \quad \lambda \leq \lambda_r \tag{12}$$

$$\lambda_r \leq \sum_c R(c, r_{src}) \cdot x^u_{cr} \tag{13}$$

$$\lambda_r \leq \sum_c R(c, r_{dst}) \cdot x^d_{cr} \tag{14}$$

$$\sum_r x^u_{cr} + \sum_r x^d_{cr} \leq 1 \tag{15}$$

The objective (11), together with the constraint (12), guarantees the max-min fairness for per-session throughput. Constraint (13) and (14) bound the uplink and downlink throughput, respectively. Constraint (15) dictates that one subcarrier can be assigned to at most one link of all sessions.

Recall that the above formulations are based on FDD. However, it is straightforward to extend them to TDD based systems. In TDD mode, it is reasonable to assume that the uplink rate of each session equals to the session throughput which is specified by the user's QoS requirement. Correspondingly, the optimization objective can be the minimization of total power consumption, or maximization of the number of admissible sessions.

IV. The Heuristic Assignment Algorithm

The above CADSA and NO-CODE mixed-integer problems are NP-hard in general. Conventional exact solutions, such as branch and bound [12], can only handle small scale problems with tens of sessions and subcarriers. Although meta-heuristics like simulated annealing [12] may provide acceptable approximate solutions to large scale problems, they typically take a long time to converge, which is undesirable since in practice the subcarrier allocation algorithm needs to be called every few milliseconds. Here we propose polynomial time heuristic algorithms that can be applied to the base station of real wireless switching networks.

The basic idea for the heuristic CADSA algorithm is to choose the subcarrier with the highest channel gain for each link, and put those sessions with network coding opportunities to a higher priority, such that the performance gains over non-coding schemes can be fully explored. A sketch of the scheme is shown in **Algorithm 1**. The algorithm runs in a round based manner. In each round, each session first chooses the best subcarrier for its uplink, provided that its current uplink rate is less than or equal to the downlink rate. Then, the pairs of sessions with coding opportunities choose the best subcarriers for their downlinks. The best subcarrier should maximize the shared downlink rate of the two sessions, while minimizing their difference. After that, those sessions with no coding opportunities choose the subcarriers that maximize their downlink rate. To ensure fairness, all sessions are randomly permutated in each round. The algorithm terminates when no more subcarrier can be assigned in a round. The main computational load of **Algorithm 1** is dominated by searching for the best coding opportunities, whose complexity is $O(E \cdot N^2)$, where E is the number of subcarriers and N is the number of sessions that have coding opportunities.

Algorithm 1 The suboptimal Coding Aware Dynamic Subcarrier Assignment (CADSA) algorithm.

repeat
  for all session r **do**
    if current uplink rate $\leq$ downlink rate **then**
      Assign the best subcarrier to the uplink of r
    end if
  end for
  Let $M_r =$ uplink rate $-$ downlink rate of session r. ϕ is the set of sessions that have coding opportunities.
  for all session $r \in \phi, M_r > 0$ **do**
    Initialize $R_{max} = 0, D_{min} =$ unlimited.
    for all $s > r$ and s can be encoded with r **do**
      for all unused subcarrier c **do**
        $T = \min(R(c, r_{dst}), R(c, s_{dst}))$,
        $D = |R(c, r_{dst}) - R(c, s_{dst})|$
        if $T > R_{max}$ OR
        ($T == R_{max}$ and $D < D_{min}$) **then**
          $R_{max} = T, D_{min} = D, \zeta = c, \epsilon = s.$
        end if
      end for
    end for
    Encode session r and ϵ. Assign subcarrier ζ to both.
  end for
  for all session $r \notin \phi$ **do**
    Allocate the best unused subcarrier to its downlink.
  end for
until No subcarrier is allocated in the last loop.

We proceed to introduce a suboptimal solution to the NO-CODE optimization framework. We revise **Algorithm 1** such that in each round no network coding opportunities are searched, and the uplink and downlink of each session are assigned the best available subcarriers, respectively. In essence, this is a natural extension of existing downlink-only assignment heuristics [3], [8].

V. Performance Evaluation

In this section, we investigate the performance of the heuristic CADSA **Algorithm 1** in comparison with the optimal solution, as well as the non-coding schemes.

A. Experiment Setup

The key of our experiment settings is to derive the achievable data rate of a subcarrier when it is allocated to an arbitrary SS. This requires computing the corresponding SNR value, and mapping the SNR to achievable rate. To generate realistic results, we adopt empirical parameters to model the wireless fading environment, and configure the OFDMA protocols according to the 802.16 specification [1].

Simulating the wireless environment involves modeling the channel impairment due to large scale fading effects (path loss and shadowing) and small scale fading effects. The channel impairment due to large scale fading is modeled by the log-normal equation [13]:

$$\text{Channel gain (dB)} \; = K + 10\alpha \log(d) + X \tag{16}$$

where d denotes the distance between the BS and the SS; K is a constant equal to 46.7dB in 5GHz outdoor environment; the path loss exponent α is set to 2.4; X is a zero-mean Gaussian random variable with empirical variance 5.4dB [4]. We assume the shadowing loss varies on the time scale of 0.1 second.

The small scale fading effects are caused by movement of the SS in multipath environment, and can be modeled by the Rayleigh fading process. The resulting channel gain varies over the whole frequency band, and the same subcarrier may experience different gains at different time stamps. The frequency selective property is characterized by an exponential power delay profile with delay spread 15 μs. The time selective nature is captured by the Doppler spread, which depends on the SS's speed (throughout the simulation, the SSs are moving according to the random waypoint model, with mean speed 2m/s and pause period 0.1s). The combined complex gain is generated using an improved Jakes-like method [13], which models the Rayleigh fading, the frequency correlation between adjacent subcarriers and the time correlation for each subcarrier.

Without loss of generality, we choose the following subset of configurations from the 802.16d wirelessMAN-OFDMA specifications [1]. The system bandwidth is 7 MHz, centered around the 5 GHz frequency, and equally shared by all subcarriers. The maximum number of data subcarriers is 1536; subcarrier spacing is $3\frac{29}{32}$ kHz; symbol period T_s is $264\mu s$; frame length T_f is 2 ms. The bit rate of each data subcarrier is computed as: $R = \frac{b_m c_r}{T_s}$, where b_m is the number of bits in a modulation symbol and c_r is the coding rate. Each subcarrier adaptively chooses the modulation type according to its current SNR. Available modulation schemes include QPSK$\frac{1}{2}$ (coding rate), QPSK$\frac{3}{4}$, 16QAM$\frac{1}{2}$, 16QAM$\frac{3}{4}$, 64QAM$\frac{1}{2}$, and

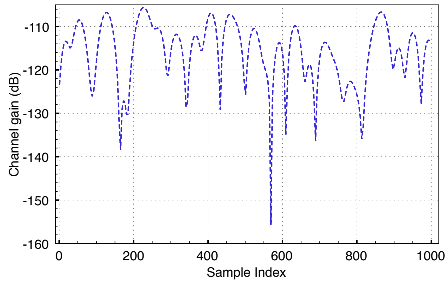

Fig. 2. Time selective characteristic of a subcarrier (sample period is 2ms).

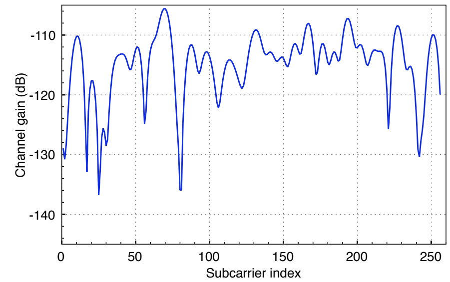

Fig. 3. Frequency selective characteristic of the channel at a certain time.

64QAM$\frac{3}{4}$. The corresponding SNR thresholds are 6.0dB, 8.5dB, 11.5dB, 15dB, 19dB and 21dB [1]. When computing SNR, the BS transmission power, noise temperature and noise figure are 1W, 290K and 7dB, respectively. Both the BS and the SSs use omni-directional single-antenna transceivers. We only focus on the single-cell case, *i.e.*, interferences from neighboring cells are omitted.

B. Experiment Results

Under the above settings, snapshots of the channel fading characteristics are illustrated in Fig. 2 and Fig. 3. We observe that the channel coherence time is much longer than T_f. Thus it is reasonable to adjust the subcarrier assignment for every few frames. The subcarriers experience diverse channel conditions at the same time, making it promising to adaptively match the subcarriers to the links.

We compare three subcarrier allocation schemes: the coding aware dynamic subcarrier assignment (CADSA) algorithm, adaptive subcarrier assignment without network coding (NO-CODE), and the randomized subcarrier allocation mechanism (referred to as RAND). Similar to the scheme in 802.16, the RAND algorithm randomly allocate an equal number of subcarriers to each uplink and downlink, and chooses the modulation for each subcarrier according to its SNR value. Since the optimal solution for CADSA and NO-CODE cannot be obtained for large scale scenarios using optimization software, we evaluate their LP-relaxations instead. We relax the integer constraints on the variables x^u_{cs}, x^d_{cs} and y^c_{rs}, allowing them to be real numbers in $[0, 1]$. The resulting linear-programming solutions impose upper bounds on the original mixed-integer programs.

1) Throughput comparison: We focus on the scenario where 8 mobile SSs are located in a circular cell with 0.5km radius. We randomly start 20 pairwise sessions with constant bit rate traffic. To reduce the computation load of the linear programs, we only use 256 data subcarriers (around the central frequency) of the whole frequency band. We compute the network capacity, *i.e.*, the aggregate network throughput of all sessions, over a period of one second.

As shown in Fig. 4, the network capacity of CADSA is consistently around 30% higher than that of NO-CODE. Owning to the adaptive subcarrier selection, both CADSA and NO-CODE significantly outperform the RAND. Note that the throughput of heuristic CADSA and NO-CODE can approach the optimal values. This is at the cost of fairness, *i.e.*, there can be a certain gap between the max and min throughput of all sessions. To quantify the difference in fairness, we compute the Jain's fairness index for all the above schemes. Denote the throughput of session i as T_i, then the fairness index is $F = \frac{(\sum_i^n T_i)^2}{n \sum_i^n T_i^2}$. From Fig. 5, we see that the LP solutions tend to achieve full fairness (*i.e.*, $F = 1$). The intuition behind is that the optimal algorithm can reduce the difference in throughput by switching subcarriers from high-throughput sessions to low-throughput sessions. Remarkably, the fairness of the heuristic CADSA is similar to NO-CODE, and only around 1% lower than the optimum.

2) Influence of path-loss diversity: In general, the adaptive subcarrier assignment algorithms perform better than RAND in the scenarios with diverse channel gains, *i.e.*, the path-losses of different SSs vary a lot. However, for coding aware subcarrier assignment, it is preferable to encode the two downlinks with similar channel quality, and assign the same subcarriers to them. Otherwise the downlink with worse channel condition will undermine the shared downlink rate. In Fig. 6, we explore the influence of path-loss diversity on time-averaged network capacity. Path-loss diversity is reduced when we decrease the cell radius (or equivalently increase transmission power), since the SSs' difference in distances to the base station is reduced. We observe that with homogeneous channel gains, the coding gain approaches the $\frac{1}{3}$ bound. When the SSs experience considerably different channel conditions, the advantage of network coding over the NO-CODE algorithm diminishes. Noticeably, both dynamic assignment algorithms (CADSA and NO-CODE) keep high throughput gain over the RAND, even under severe channel conditions. An additional observation is that the throughput of heuristic algorithms approach the optimum with larger diversity. This is again because the heuristics trade off fairness for throughput, *i.e.*, the fairness indices of heuristic algorithms deviate from the optimal solution as we increase the cell radius (Fig. 7).

Note that in the above experiments, we assume the sessions are paired so that each session is interested in exchanging information with another one, thus a coding opportunity exists for each session. In practice, not all sessions may have coding opportunities, therefore the gains of network coding also depend on the portion of sessions that can be encoded.

3) Overhead issue: One of the advantages of CADSA is that no additional overhead is introduced compared with NO-CODE. In the original XOR coding protocol [5], [6], the identities of the coded frames and corresponding transmitters must be explicitly included in the header field. However, for

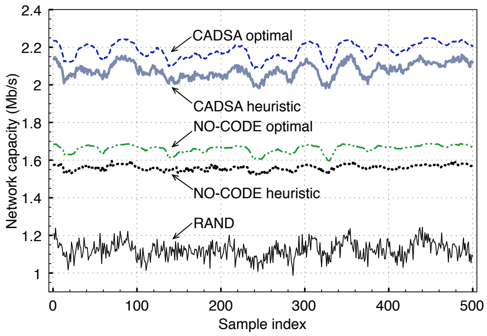

Fig. 4. The network capacity as a function of time (sample period is 2ms).

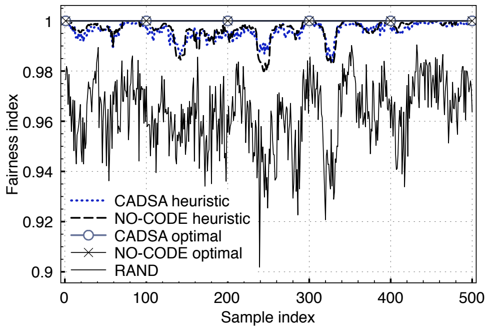

Fig. 5. Fairness index as a function of time (sample period is 2ms).

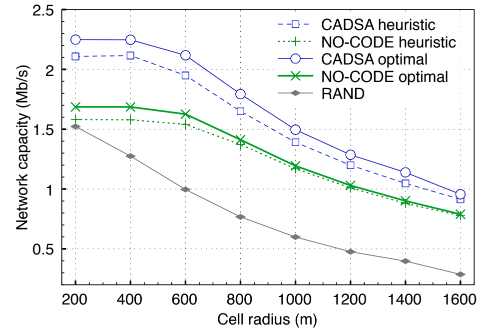

Fig. 6. Influence of path-loss diversity on the network capacity.

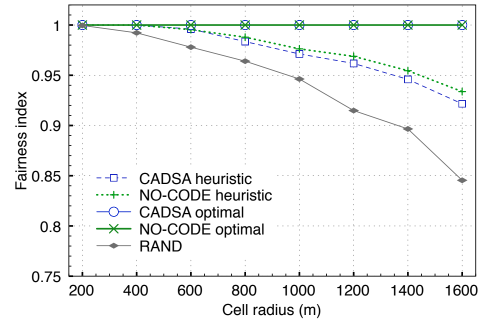

Fig. 7. Influence of path-loss diversity on fairness.

coding aware subcarrier assignment in OFDMA systems, such information is implicit. Since exactly two downlink sessions (if any) can be encoded, the pairs of sessions that share the same downlink subcarriers are exactly the encoded pairs. The subcarrier assignment information can be found in the signaling field (DL-MAP and UL-MAP [1]) in each OFDMA frame. In addition, the encoding operation is on a per-frame, rather than per-packet basis, requiring interactions between the network layer and lower layers. At the downlink receiver side, each frame can be decoded by XORing it with the latest frame that it successfully sent out since there is no backlog at the BS (uplink and downlink rate are the same).

Admittedly, the dynamic subcarrier allocation introduces non-negligible overhead when compared with RAND. It has been observed that the overhead may compromise the benefits of adaptive subcarrier allocation, especially when a large number of subcarriers are involved [4]. Fortunately, the overhead can be significantly reduced by coarse-grained adaptations (see, *e.g.*, [4]). Such overhead reduction techniques apply to our coding aware subcarrier allocation scheme as well.

VI. Conclusion

In this paper, we have designed a cross layer scheme that integrates network coding and dynamic subcarrier assignment in OFDMA wireless networks. We have formulated the optimal coding aware subcarrier assignment scheme, and proposed a polynomial time suboptimal algorithm. Our simulations in the frequency selective fading environment and under 802.16-like settings have demonstrated that network coding can more efficiently utilize the available subcarriers. The coding-aware scheme results in considerably higher network throughput without causing additional overhead when compared with adaptive assignment algorithms without network coding. In a similar vein, it may serve as a resource allocation method for other multichannel networks and their variants, such as multi-radio, MIMO and CDMA based wireless switching networks.

References

[1] IEEE Standard, "802.16™: Air Interface for Fixed Wireless Access Systems," 2004.

[2] C. Wong, R. S. Cheng, K. Letaief, and R. Murch, "Multiuser OFDM with Adaptive Subcarrier, Bit, and Power Allocation," in *IEEE JSAC*, vol. 17, no. 10, Oct 1999.

[3] Z. Shen, J. G. Andrews, and B. L. Evans, "Adaptive Resource Allocation in Multiuser OFDM Systems With Proportional Rate Constraints," *IEEE Transactions on Wireless Communications*, vol. 4, no. 6, 2005.

[4] J. Gross, H. Geerdes, H. Karl, and A. Wolisz, "Performance Analysis of Dynamic OFDMA Systems with Inband Signaling," in *IEEE JSAC*, vol. 24, no. 3, Mar 2006.

[5] Y. Wu, P. A. Chou, and S.-Y. Kung, "Information Exchange in Wireless Networks with Network Coding and Physical-Layer Broadcast," in *Proc. of CISS*, 2005.

[6] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, "XORs in The Air: Practical Wireless Network Coding," in *Proc. of ACM SIGCOMM*, July 2006.

[7] J. Gross and M. Bohge, "Dynamic Mechanisms in OFDM Wireless Systems: A Survey on Mathematical and System Engineering Contributions," TU-Berlin, Tech. Rep. TKN-06-001, May 2006.

[8] W. Rhee and J. M. Cioffi, "Increase in Capacity of Multiuser OFDM System Using Dynamic Subchannel Allocation," in *Proc. of IEEE VTC*, 2000.

[9] W. Chen, K. Letaief, and Z. Cao, "A Cross Layer Method for Interference Cancellation and Network Coding in Wireless Networks," in *Proc. of IEEE ICC*, 2006.

[10] S. Sengupta, S. Rayanchu, and S. Banerjee, "An Analysis of Wireless Network Coding for Unicast Sessions: The Case for Coding-Aware Routing," in *Proc. of IEEE INFOCOM*, 2007.

[11] M. Sternad and D. Aronsson, "Channel Estimation and Prediction for Adaptive OFDMA/TDMA Uplinks Based on Overlapping Pilots," in *Proc. of IEEE ICASSP*, 2005.

[12] G. L. Nemhauser and L. A. Wolsey, *Integer and Combinatorial Optimization*. Wiley-Interscience, 1988.

[13] J. K. Cavers, *Mobile Channel Characteristics*. Kluwer Academic Publishers, 2000.