A Game-Theoretic Framework for Resource Allocation in IEEE 802.16j Transparent Relay Networks

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Abstract. This paper focuses on downlink resource allocation in IEEE 802.16j transparent relay networks. A game theoretical formulation is derived where a resource allocation problem is represented as a two-stage bargaining game. Based on game formulation and solutions, the proposed approach not only provides improved performance but also supports fairness among the inter-class and intra-class users according to their heterogeneities in terms of the rate requirement, channel conditions, and link types. The simulation results confirm that the proposed scheme achieves a tradeoff between effective data rate and proportional fairness while also outperforming the static scheme and guaranteeing the rate requirements.

Keywords: OFDMA, 802.16j networks, game theory, resource allocation, transparent relay.

1 Introduction

Next generation (i.e.,4G) broadband wireless access networks are designed to provide high data rate to support fixed and mobile users having different quality of service (QoS) requirements. The system based on IEEE 802.16e standards is among leading candidates for 4G wireless networks. In such networks, a single base station covers a cellular area with radius of one mile. However, its initial field trials have limited coverage and poor service for indoor as well as cell boundary users. To address drawbacks, the IEEE 802.16j standard [1] has been developed to extend 802.16e to achieve coverage extension and capacity enhancement with full backward compatibility to 802.16e Mobile Stations (MSs).

The IEEE 802.16j standard [1] specifies that a relay station which supports multi-hop relay operations can operate in two different modes: transparent and non-transparent modes. In the transparent relay mode, a transparent RS is not allowed to transmit control messages such as preamble, FCH, UL/DL-MAP and DCD/UCD. Instead, the BS directly sends control messages to MSs. Hence, the scheduling for both uplink and downlink transmission are performed at the BS centrally. In doing this, the control overhead is reduced and the end-to-end throughput is improved. However, the transparent mode only supports when all MSs are within the coverage range of the BS. In contrast, a non-transparent RS is designed to support MSs which are out of the BS

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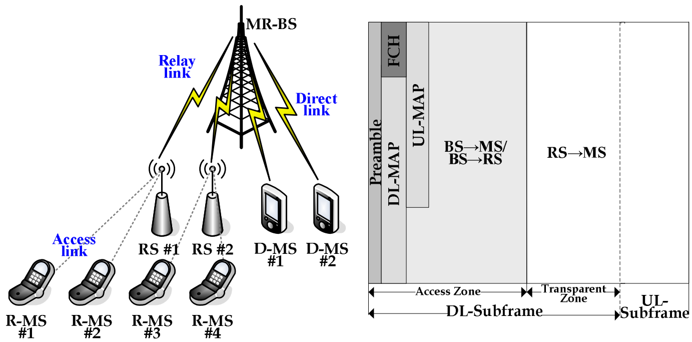

(a) (b)

Fig. 1. IEEE 802.16j transparent relay networks: (a)topology and (b) frame structure

coverage range by transmitting/receiving control messages as well as data packets to/from those MSs. In the non-transparent mode, the transmission scheduling can be done either in a centralized or a distributed way. For both operating modes, resource allocation is one of the most important issues concerns the system throughput. Therefore, this study focuses on the resource allocation issue of 802.16j transparent relay systems and leaves the problem of non-transparent relays as the future work.

Figure 1 shows the topology and the frame structure of an 802.16j transparent relay network. In Fig. 1(a), the one-hop links between the multi-hop relay base station (MR-BS) and the transparent relay stations (T-RSs) are referred to as *relay links*, while the links between the T-RSs and the relay mobile stations (R-MSs) are referred to as *access links*. The links between the MR-BS and the directed mobile stations (D-MSs) are *direct links*. As shown in Fig. 1(b), the 802.16j transparent relay frame is comprised of the downlink and uplink subframes. Each downlink subframe is further partitioned into access and transparent zones. The MR-BS uses the access zone to transmit packets to D-MSs and T-RSs. The packets received in the access zone by a T-RS are subsequently relayed to R-MSs in the transparent zone.

Although the resource allocation problem of relay networks has been extensively investigated in [2-4], their solutions are under a fixed zone partitioning structure which ignores the 802.16j specifications. Applying these solutions under a heavy network load will result in poor system utilization due to their inability to adapt to varying network dynamics (e.g., varying traffic load to D-MSs and R-MSs, various MS channel conditions, and differing minimum reserved rates of service flows). Several resource allocation schemes based on dynamic zone partitioning (DZP) have also been proposed for relay networks [5-7]. However, the scheme proposed in [5] does not take into account the various minimum reserved traffic rates (MRTR) of different service flows in the network. Those presented in [6-7] are distributed approaches, and are unsuitable for centrally-oriented networks such as 802.16j transparent relay networks.

Recently, game theory has been widely used for resource management weighing different network constraints such as power, QoS requirements, channel conditions, etc. In particular, many studies have focused on using a non-cooperative game approach to model the bandwidth allocation problem in wireless networks. In [8], a game-theoretic based scheduler for bandwidth provisioning in 4G BWA technologies is presented. This approach simultaneously controls network congestion and fairness while providing differentiated QoS guarantees. In [9], the hierarchical bandwidth sharing problem in dynamic spectrum access is formulated as an interrelated market model from a microeconomics perspective. A similar approach has been used in [10]-[12] with varying definitions of the utility function and different network constraints. However, it is well known that Nash equilibrium is Pareto inefficient and the pricing mechanisms proposed only provide some Pareto improvements [13].

In recently years, there has been an increasing trend to use the axiomatic bargaining theory of cooperative game theory to examine resource allocation problems [13-15]. Axiomatic bargaining theory provides a good analytical framework to derive a unique desirable operation point that is fair and Pareto optimal. Accordingly, this study presents a DZP resource allocation scheme based on a two-stage bargaining game for accomplishing downlink transmission under varying network dynamics in a 802.16j transparent relay network. The game formulation is based on a bottom-up model where player utility functions in each stage reflect the corresponding bargaining solutions. According to game formulation and solutions, a tradeoff between effective data rate and proportional fairness for relay systems is provided. Simulation results show the resulting resource allocation is both fair and efficient among inter-class and intra-class users. To the best of the authors' knowledge, the proposed scheme represents the first attempt to present a game formulation for the DZP problem in 802.16j transparent relay systems.

2 Dynamic Zone Partitioning Game

In developing the DZP resource allocation scheme, this study assumes the 802.16j transparent relay network utilizes partial usage of sub-carriers (PUSC) mode in orthogonal frequency division multiple access (OFDMA) systems and operates under heavy traffic load environment. It is further assumed that the downlink subframe contains N resource slots, comprising N_{az} access zone resource slots and N_{tz} transparent zone resource slots. Finally, an assumption is made that the system consists of K service classes, indexed by the set $\Omega=\{1,2,\ldots,K\}$. For each class $k\in\Omega$, the corresponding service flows are denoted by the set $\Phi_k=\{1,2,\ldots, I_k\}$.

2.1 Two-Stage Bargaining Game

The proposed DZP resource allocation scheme is based on a two-stage bargaining game. In the first stage, resource allocation between different service classes is modeled as an *inter-class* bargaining game, in which each player represents a particular service class, i.e., a class of service flows with the same minimum reserved rate. The strategy for a player k, where all $k\in\Omega$, is the number of resource slots allocated for transmission in a downlink subframe. The payoff for service class k is evaluated using a utility parameter u_k, defined as a function of the corresponding class-level performance.

To ensure an efficient and fair distribution of the resource slots amongst all the service classes, the solution of the bargaining game is obtained using Nash Bargaining Solution (NBS). The NBS is defined as follows:

Definition 1 Nash Bargaining Solution (NBS): *Let* $C = \{k\in \Omega \mid \exists u\in U, u_k > u_{dis,k}\}$ *be the set of players(i.e., classes) which can achieve a utility strictly greater than the* *disagreement utility $u_{dis,k}$. Under the five general axioms* [15], *Nash showed that the unique NBS (i.e., $\phi(u^*, u_{dis,k})$) is that which maximizes the Nash Product, i.e.,*

$$\phi(u^*, u_{dis,k}) \in \arg\max_{u>u_{dis}} \prod_{k=1}^{K} (u_k(N_k) - u_{dis,k}) \ , \tag{1}$$

where $\sum_{k=1}^{K} N_k \le N$, $u_k(.)$ is the utility function for class k, and N_k is the total number of resource slots allocated to class k.

Once each class has obtained its solution (i.e., N^*_k) by performing a local search method, the second stage of the bargaining game is performed to distribute the resource slots allocated to each class amongst all service flows within the class. In other words, the second stage of the bargaining game is an *intra-class* bargaining problem. For a service class k, each of the service flows within the class represents a player in the game. The strategy of each player i (where $i \in \Phi_k$) is the number of allocated resource slots received for its downlink transmission. Importantly, in obtaining the solution to the game, each player must receive an equal payoff in every frame since each service flow has the same minimum reserved rate. To achieve this goal, Egalitarian Bargaining Solution (EBS) [16] is used to obtain the bargaining solution. The EBS is defined as follows.

Definition 2 (Egalitarian Bargaining Solution (EBS)): *The total number of allocated resource slots for class k is N^*_k. Thus, $N^*_{k,i}$ is the EBS for a service flow i in the intra-class bargaining game if and only if the numbers of allocated resource slots received by any two players p and v satisfy*

$$\xi_{k,p}(N^*_{k,P}) = \xi_{k,v}(N^*_{k,v}),\ \forall p,\ v \in \Phi_k,\ p \ne v\,, \tag{2}$$

where $\sum_{i=1}^{I_k} N^*_{k,i} = N^*_k$ and $\xi_{k,i}(.)$ is the utility function of service flow i in class k.

2.2 Utility Formulation for Two-Stage Bargaining

When conducting a bargaining process in two stages, a critical problem is that of modeling the player utility functions in each stage in such a way as to reflect the corresponding bargaining solutions. In the proposed DZP scheme, the aim is to provide an effective throughput-fairness allocation for all service flows under varying network dynamics. Thus, it is reasonable to take a bottom-up approach to model the utility functions in the two-stage bargaining game by first deriving the bargaining power of each service flow within a class and then deriving the overall bargaining power of the class.

1) Intra-class Bargaining Utility Formulation: Let $R_k=\{r_{k,1,s}, r_{k,2,s}, \ldots, r_{k,I,s}\}$ for all $s\in\{\text{D-MS, R-MS}\}$ be the set of per slot transmission rates for the service flows in class k. To obtain EBS for the different service flows within the class, the utility function (i.e., the payoff) for service flow i in the current frame is assumed to be its amount of data which can be sent in this frame, i.e.,

$$\xi_{k,i}(N_{k,i,s}) = r_{k,i,s} \cdot N_{k,i,s},\ i \in \Phi_k\,, \tag{3}$$

where $N_{k,i,s}$ is the number of resource slots allocated to the service flow i. If flow i is destined for a D-MS, the per slot transmission rate $r_{k,i,D}$ is easily obtained from the feedback received at the MR-BS from the D-MS. However, if flow i is destined for an R-MS (denoted as R-MS i), the per slot transmission rate is given by combining the transmission rate on the relay and access links, i.e.,

$$r_{k,i,R} = 1/((r_{k,i,B\_R})^{-1} + (r_{k,i,R\_M})^{-1}) \ , \tag{4}$$

where r_{k,i,B_R} is the per slot transmission rate from the MR-BS to the T-RS associated with R-MS i, and r_{k,i,R_M} is the per slot transmission rate from T-RS to R-MS i. This utility formulation applied in Eq. (2) guarantees EBS fairness amongst the different service flows within a class.

2) Inter-class Bargaining Utility Formulation: In formulating the utility function of each class in the inter-class bargaining stage of the game, the transmission rate of a class is defined as follows.

Definition 3 (Class Transmission Rate (CTR)): *$r_{CTR,k}$ is the class transmission rate for class k and is equal to the summation of the amount of data sent in this frame of all service flows within the class divided by the total number of resource slots θ_k allocated to the class, i.e.,*

$$r_{CTR,k} = \sum_{i=1}^{I_K} \frac{\left(\xi_{k,i}(N_{k,i,s})\right)}{\theta_k} , \tag{5}$$

where $\theta_k = \sum_{i=1}^{I_K} \left(\xi_{k,i}(N_{k,i,s}) / (r_{k,i,s})\right)$.

Since the EBS of the intra-class bargaining game guarantees that each flow within class k has the same payoff, the class transmission rate is obtained as follows:

$$\begin{aligned} r_{CTR,k} &= \frac{\left(\xi_{k,i}(N_{k,i,s})\right) \times I_k}{\theta_k} \\ &= \frac{\left(\xi_{k,i}(N_{k,i,s})\right) \times I_k}{\sum_{i=1}^{I_k} \left(\xi_{k,i}(N_{k,i,s})/(r_{k,i,s})\right)} = \frac{I_k}{\sum_{i=1}^{I_k} 1/(r_{k,i,s})} . \end{aligned} \tag{6}$$

Therefore, to measure the achievable utility of a particular class in each frame, the following logarithmic utility function is introduced:

$$u_k(N_k) = \log(r_{CTR} \cdot N_k - \sum_{i=1}^{I_k} \eta_{\min,k,i} - \sum_{i=1}^{I_k} c_{k,i}) , \tag{7}$$

where $\eta_{min,k,i}$ and $c_{k,i}$ are the minimum guaranteed amount of data and the control message overhead (i.e., Preamble and DL/UL MAP) should be sent per frame for service flow i in class k in the current frame, respectively. Note that $\eta_{min,k,i}$ can be derived from its minimum reserved traffic rate.

2.3 Zone Partition

Once the inter-class bargaining stage has determined the allocated resources N^*_k for each class k, the number of transmission slots $N^*_{k,i,s}$ required for service flow i associated with class k can be determined by Eq. (2) and Eq. (3) as follows:

$$N^*_{k,i,s} = \left\lfloor N'_k \cdot \left(r^{-1}_{k,i,s} \Big/ \sum\nolimits_{i=1}^{I_k} r^{-1}_{k,i,s} \right) \right\rfloor, \tag{8}$$

where $N'_k = N^*_k - \sum_{i=1}^{I_k}\left(c_{k,i} / r_{k,i,s}\right)$. If flow i is destined to an R-MS, $N^*_{k,i,R}$ is further divided into $N^*_{k,i,R,az}$ and $N^*_{k,i,R,tz}$, i.e., the number of resource slots required for R-MS i downlink transmission in the access zone and the transparent zone, respectively. $N^*_{k,i,R\text{-},az}$ and $N^*_{k,i,R,tz}$ are expressed as

$$N^*_{k,i,R,az} = \left\lfloor N^*_{k,i,s} \cdot \left(r_{k,i,R\_M} \Big/ \left(r_{k,i,B\_R} + r_{k,i,R\_M} \right) \right) \right\rfloor \tag{9}$$

and

$$N^*_{k,i,R,tz} = \left\lceil N^*_{k,i,R,az} \cdot \left(r_{k,i,B\_R} / r_{k,i,R\_M} \right) \right\rceil. \tag{10}$$

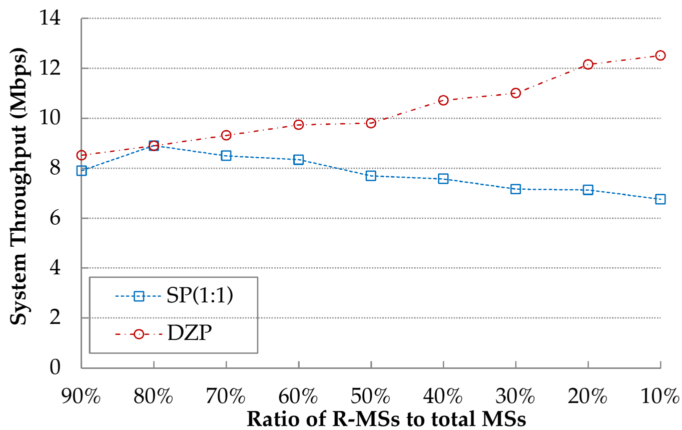

Fig. 2. System throughput for various R-MSs to total MSs ratios

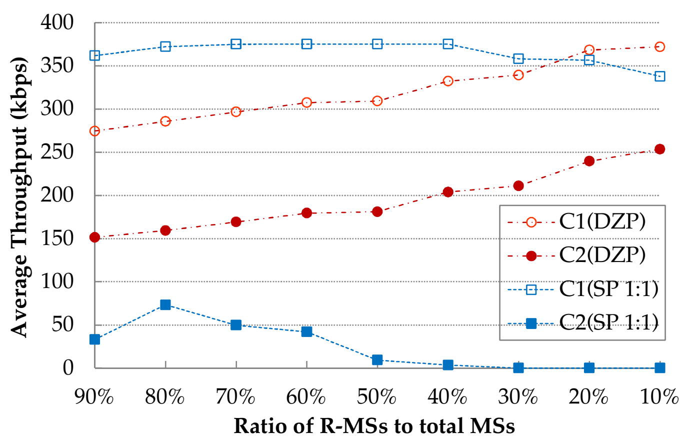

Fig. 3. Average Throughput for various R-MSs to total MSs ratios

As a result, in each downlink sub-frame, the exact number of resource slots required for data transmission in the access zone and transparent zone are given respectively by

$$N^{*}_{az} = \sum_{k=1}^{K} \sum_{i=1}^{I_k} \left(N^{*}_{k,i,D} + N^{*}_{k,i,R,az} + \left(c_{k,i} / r_{k,i,s} \right) \right) \tag{11}$$

and

$$N^{*}_{tz} = \sum_{k=1}^{K} \sum_{i=1}^{I_k} \left(N^{*}_{k,i,R,tz} \right). \tag{12}$$

Once N^{*}_{az} and N^{*}_{tz} have been derived, the partitioning of the downlink sub-frame into the access zone and the relay zone is easily achieved.

3 Simulation Results and Analysis

The performance of the proposed DZP scheme was evaluated using an 802.16j transparent relay simulation model constructed using QualNet Simulator 4.5 [17]. The simulation model included a single cell comprising a MR-BS, six T-RSs and 40 randomly-distributed MSs. The simulations assumed 20 MHz bandwidth, an OFDMA frame size of 20 ms, and the downlink-to-uplink ratio was specified as 2:1. Two different service classes were simulated, namely class 1 (C1) and class 2 (C2). Each MS has a service flow which has an equal probability of being in either C1 or C2. The packet arrival at MR-BS was modeled as a Poisson process. The traffic rates for C1 and C2 service flows were specified as 375 kbps and 256 kbps, respectively. Finally, the minimum reserved traffic rates for C1 and C2 were respectively set at 256 and 128 kbps. The performance of the proposed bargaining game-based DZP scheme was compared with Strict Priority (SP) scheme [18]. Note that SP scheme is regarded as a static scheme which has a fixed boundary between the access zone and the transparent zone with a ratio of 1:1.

In addition, to measure the user fairness within a class, the fairness metric uses the traditional Jain's Fairness Index (FI) [19].

$$\mathrm{FI} = \frac{\left(\sum_{i=1}^{N} Thr_i \right)^2}{\left(N \sum_{i=1}^{N} Thr_i^2 \right)} \tag{13}$$

where Thr_i is the average throughput of service flow i in a class and $0 \le \mathrm{FI} \le 1$.

Figure 2 shows the variation of the system throughput with respect to the ratio of R-MSs to total MSs. It can be seen that the system throughput of the SP scheme decreases with the ratio of R-MSs to total MSs. In contrast to the SP scheme, the system throughput of the proposed DZP scheme increases with increasing ratio of R-MSs to total MSs. The results show the proposed DZP scheme improves the capacity of the SP approach by up to 33% on average. This is because when the ratio of R-MSs to all MSs increases, the R-MSs need more resource slots to transmit data packets. By employing the proposed DZP scheme, the boundary between the access zone and the transparent zone can be adaptively adjusted to improve resource utilization according to the traffic rate requirements of MSs with different link types.

Figure 3 plots the C1 and C2 average throughputs of the proposed DZP scheme compared with those of SP with varying ratio of R-MSs. It can be observed that the C2 average throughput of the SP scheme is lower than its minimum reserved traffic rates due to the essence of the SP scheme. Since the proposed DZP scheme employs the NBS solutions at the first stage bargaining game, the average throughput of each class in DZP always meets the minimum reserved traffic rate required by each class despite the fact that the service flows are receiving lower allocations than the scenarios with a lower ratio of R-MSs. The SP scheme favors the MSs of C1, where C1 always has higher priority to get requested bandwidth before bandwidth being distributed to the MSs of C2. The average throughput of the proposed DZP is superior to that of the SP scheme when the ratio of R-MSs is greater than 30%. The reason is that the proposed DZP scheme is able to adaptively select a suitable zone boundary between the access zone and the transparent zone.

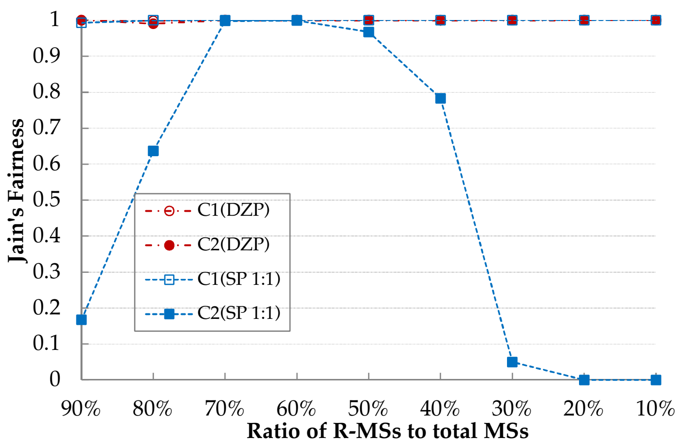

Fig. 4. Jain's Fairness for various R-MSs to total MSs ratios

Figure 4 illustrates the variation of the class fairness with respect to the ratio of R-MSs to total MSs. It shows that both C1 and C2 in the proposed DZP have almost perfect fairness among all service flows in the class while the SP approach is not fair for the C2 service flows. This is a result of the EBS of the second stage game formulation in the proposed DZP.

4 Conclusion

A dynamic zone partitioning game has been presented for solving the resource allocation problem in IEEE 802.16j transparent relay networks under varying network dynamics. The proposed scheme is able to adaptively adjust the boundary between the access zone and the transparent zone in the downlink subframe. It provides a tradeoff between fairness and throughput while meeting rate guarantees to all the service flows within the system irrespective of whether they are direct or relay MSs. The simulation results have confirmed that the proposed game-theoretic-based resource allocation scheme ensures efficient and fair bandwidth distribution amongst the different service flows within the IEEE 802.16j transparent relay network.

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