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Distributed subchannel assignment in a two-hop network

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ABSTRACT

This paper studies distributed subchannel allocation in a two-hop network comprising multiple source nodes, one multi-channel relay node and one destination node. The underlying subchannel allocation problem in a relay network, when posed as a centralized allocation problem, is formulated as a three-dimensional assignment problem. Distributed subchannel allocation is studied using noncooperative game theory. A sequential game model is formulated where in first stage source nodes opportunistically select their transmission resources after which in second stage a channel-aware relay node assigns the resources in a way that maximizes the sum of utilities at the destination node. The subchannel allocation game is a potential game, possessing an implicit joint objective (potential) of the players. Numerical examples illustrate the performance of opportunistic channel allocation in an OFDMA system. Using the sequential scheme, noncooperative allocation in first link implies performance similar to that obtained by solving two consecutive assignment problems, first optimizing the allocation of subchannels in source-relay link and second in relay-destination link. Auction-based solutions to noncooperative subchannel allocation, both with fixed and variable transmit power, are presented to obtain approximate solutions to the underlying centralized resource optimization problems.

1. Introduction

Multihop networks and relay networks have been developed for a multitude of applications in wireless systems in recent years. In large-scale broadcasting systems, such as Digital Video Broadcasting (DVB) networks, relays have been used as "gap fillers" to improve network coverage [1]. Multihop relaying has been adopted recently e.g. in IEEE 802.16 (WiMax) standardization [2], and in 3GPP standardization relays are being considered for Long-term Evolution (LTE) [3]. In these systems, relay and multihop communication increase also system capacity, not just coverage.

One key problem in multiuser multihop relay networks involves channel assignment in a case where multiple source nodes attempt to establish a link to a common destination node using a common multi-channel relay node. For example, end-user devices (e.g. mobile phones) within one cell may not be able to reach a common base station or access point in a single hop due to a challenging propagation environment. Alternatively, the source node may use a short-range communication system (e.g. Wi-Fi or IEEE 802.11) while the destination node may be tuned for long-range cellular wireless standards (e.g. WiMax) on a different carrier frequency. In both of these cases, a relay node is mandatory for establishing the link and a two-hop network emerges. The task of the relay node is to assign the resources so that network performance is optimized. In the aforementioned multiuser networks, different sources need to be assigned a distinct subchannel or subcarrier in an Orthogonal Frequency Division Multiple Access (OFDMA) system [4].

As for related work, algorithms for determining the subchannel assignment, in connection with Orthogonal

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Frequency Division Multiplexing (OFDM), have been proposed in [5–7]. Publications [8,9] extended these to the case of multiple source nodes competing for a limited number of resources at the relay node. In [9] competition is applied to spatial channels both at relay node input and relay node output whereas in [8] a single-antenna system considered. Joint optimization over both links was not considered in the multi-source models in [9,8]. However, for a single-source case, a computationally efficient optimal joint optimization solution was proposed in [6] using majorization theory [10].

This paper observes that the two-hop multi-source subchannel allocation problem, when formulated as a centralized problem (as a point of comparison for noncooperative allocation), can be stated as a three-dimensional assignment problem [11]. Since the three-dimensional assignment problem is NP-hard, and solvable only for impractical small-sized networks, the performance of the centralized allocation scheme will be approximated by solving two consecutive assignment problems. However, centralized solutions do not apply in all networks. Distributed solutions are relevant e.g. in cognitive radio networks, in ad hoc networks, or in any opportunistic wireless network where a centralized resource allocator may not even exist. In such two-hop networks, the source nodes compete for the use of available subchannels (e.g. subcarriers or time slots) between the source and the relay, avoiding collisions e.g. via feedback control. We address (partly) distributed subchannel assignment in a two-hop network with one relay node between the source and the destination. In the source-relay link, distributed subchannel allocation is modelled as a noncooperative game [12] between the source nodes. The multi-channel relay node, decomposing multiple source-destination links to a two-hop system, is modelled as a network element that has access to channel state information.

In distributed allocation, we extend the work in [9,8] as follows: first, market-based subchannel allocation based on an auction model [13] is proposed. An extended auction model implies an efficient solution for joint power and subchannel allocation (whereas [9] assumed constant power). Second, different potential game models for distributed subchannel allocation are discussed. Potential games are noncooperative games possessing a potential function, formalizing an implicit joint objective of the players [14,15]. In the example case of distributed subchannel allocation the potential function in [16] (based on [17]) reduces to a simpler potential in [9] (based on [18]). The resource allocation game in a relay network is formulated as a sequential game of imperfect information[1][12].

The paper is organized as follows. Section 2 formalizes a system model for a multiuser two-hop relaying scheme. Section 3 presents noncooperative game models for distributed subchannel allocation: first, a sequential game model (without pricing) and second an auction-based model (with pricing). Numerical examples in an OFDMA setting are discussed in Section 4. Section 5 extends the allocation game to joint power and subchannel allocation and to a general utility model. In a general utility model the utility functions of the source nodes are known only by the source nodes themselves. Even in a network where centralized resource allocation would be feasible, distributed allocation can be motivated to solve the mechanism design problem of eliciting the utility functions of the users [19]. Auction-based solutions to distributed resource allocation are proposed. Section 6 concludes.

2. Signal model

Define subchannel as a time slot or as a frequency subcarrier. Consider first the subchannel allocation problem in a representative *two-hop relay* system with M source nodes and Q orthogonal subchannels in the first-hop channel and P orthogonal subchannels in the second hop channel, as depicted in Fig. 1. The complex-valued channel gain of the qth subchannel between source i and the relay (source i's first-hop channel) is denoted by $a_{i,r}[q]$. Similarly, the complex-valued gain of the pth subchannel between relay and the destination node (second hop channel) is denoted by $a_{r,d}[p]$. The relay scales the signal received in subchannel q from source i with

$$\lambda_i[q] = (|a_{i,r}[q]|^2 + \sigma_r[q]^2)^{-1/2}, \quad (1)$$

where $\sigma_r[q]^2$ denotes power of noise at the relay receiver and $|a_{i,r}[q]|$ is the amplitude of the qth subchannel gain between source i and the relay. Thereafter, the signal is retransmitted on the pth subchannel from the relay to the destination. Thus, the signal of the ith source, relayed to the destination, is given by

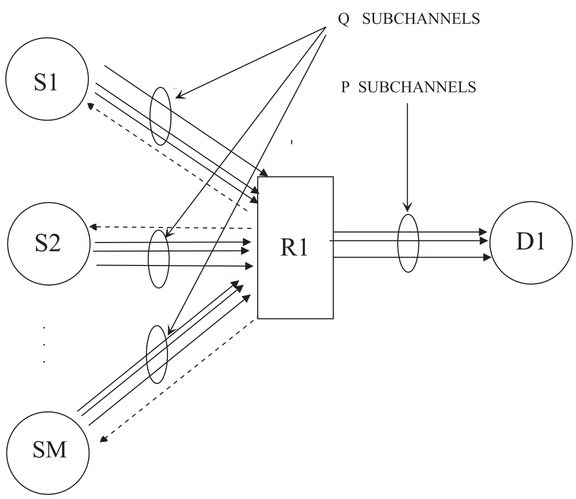

Fig. 1. Two-hop network with M source nodes (S1,...,SM), one relay node (R1) and one destination node (D1). The source nodes and the relay node select subchannels from Q and P available subchannels in the first and second hop, respectively. Relay node broadcasts a congestion signal (dashed line) to each source node to aid distributed channel assignment in the first-hop and allocates subchannels for second hop transmission.

[1] Related work in [16] has applied a sequential game with a Stackelberg structure to distributed subchannel allocation in a cognitive radio network (focusing on a single link). In [16], the Stackelberg leader is the licensee of the channel whereas in this paper the (multiple) leaders are the source nodes, noncooperatively deciding on a subchannel allocation for the source-relay link.