Resource Allocation in Wireless Relay network

Ajay Singhal, Ramesh Kumar

Abstract— **In a wireless communication system, relaying techniques can offer significant benefits in the throughput enhancement and range extension. On the other hand, cognitive radio is an interesting concept for solving the problem of spectrum availability by reusing the underutilized licensed frequency bands. In a cognitive radio network, relays can be particularly useful for reducing the transmission power at the source and thus reduce the interference to the primary users. In this paper, we study resource allocation problems for cognitive radio networks that employ relays. In this work, the transmission power of the nodes (users and relays) is the resource that we wish to allocate. The power allocation problems are formulated as non-convex non-linear programs and they do not have a structure that could guarantee the quality of the solution. We present a method of transforming the proposed optimization problems to a new formulation so that ε-optimal algorithms can be designed. In general, the transformed problem exhibits certain properties, which enable us to solve the optimization problems to a desirable accuracy by applying known global optimization techniques. We note that the global optimization techniques require significant computations to solve our proposed optimizations. Therefore, we propose low complexity heuristics that provide suboptimal solutions to the given optimization problems. The simulation results show that the performance of the heuristics is close to their respective optimal solutions.**

Index Terms— **Cognitive radio, Cooperative communication, Two-Way Relay, Multi-Way Relay, Global Optimization.**

I. Introduction

In a wireless communication system, relaying techniques can offer significant benefits in the throughput enhancement, and range extension [1]. Relaying protocols for one-way half-duplex relays are considered in [1]. Recent research on cooperative communications has shown that half-duplex two-way relaying is spectrally more efficient [2] than the conventional half-duplex one-way, [1], relaying. In two-way relaying two users can exchange data with each other using a relay in two time slots. Recently, the idea of two-way relay channel has been extended to multi-way relay channel in [3]. In this model, multiple users (≥ 2) can exchange information with each other using a relay terminal in two time slots.

Cognitive radio [4], [5], [6] is an emerging technology intended to enhance the utilization of the radio frequency spectrum. A combination of cognitive radio with cooperative communication can further improve the future wireless systems performance. However, the combination of these techniques raises new issues in the wireless systems that need to be addressed. In particular, in this thesis, we address the issue of allocating transmission power to the nodes (users and relays) subject to the constraints on the nodes' transmit powers. We provide low complexity heuristics to the proposed optimizations and compare them with their respective optimal solutions. We also study the rate and power allocation problem in a wireless relay network employing multi-way relaying and provide an optimal solution to the proposed optimization.

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II. COGNITIVE RADIO SYSTEM

Formally, a cognitive radio is defined as [7]
"A radio that changes its transmitter parameters based on the interaction with its environment"
The cognitive radio has been mainly proposed to improve the spectrum utilization by allowing unlicensed (secondary) users to use underutilized licensed frequency bands [8] [9] [10]. In reality, unlicensed wireless devices (e.g., automatic garage doors, microwaves, cordless phones, TV remote controls etc.) are already in the market [11] [12]. The IEEE 802.22 standard for Wireless Regional Area Network (WRAN) addresses the cognitive radio technology to access white spaces in the licensed TV band. In North America, the frequency range for the IEEE 802.22 standard will be 54–862 MHz, while the 41–910MHz band will be used in the international standard [9]. Table 1.1 shows the IEEE 802.22 system parameters, e.g., frequency range, bandwidth, modulation types, maximum transmit power ratings, multiple access schemes, etc. [13].
In the context of cognitive radio, the Federal Communications Commission (FCC) recommended two schemes to prevent interference to the television operations due to the secondary (unlicensed) users. These are listen-before-talk and geo-location/database schemes [11] [12]. In the listen-before-talk scheme, the secondary/unlicensed device senses the presence of TV signals in order to select the TV channels that are not in use. In geo-location/database scheme, the licensed/unlicensed users have a location-sensing device (e.g., GPS receiver etc.) The locations of primary and secondary users are stored in a central database. The central controller (also known as spectrum manager) of the secondary/unlicensed users has the access to the location database.

Parameters	**Specification**	**Remarks**
Frequency range	54-862 MHz	TV band
Bandwidth	6MHz,7 MHz, 8 MHz	
Modulation	16-QAM, 64-QAM	
Transmit power	4W	For USA, may vary in other regulatory domains
Multiple access	OFDMA	

Table 1.1 IEEE 802.22 system parameters

The main functions of cognitive radio to support intelligent and efficient utilization of frequency spectrum are as follows:

A. Spectrum sensing

Spectrum sensing determines the status of the spectrum and activity of the primary users [9] [4]. An intelligent cognitive radio transceiver senses the spectrum hole without interfering with the primary users. Spectrum holes are the frequency bands currently not used by the primary users. Spectrum sensing is implemented either in a centralized or distributed manner. The centralized spectrum sensing can reduce the complexity of the secondary user terminals, since the centralized controller performs the sensing function. In distributed spectrum sensing, each mobile device (secondary user terminal) senses the spectrum independently. Both centralized and distributed decision-making is possible in distributed spectrum sensing [9]. The central controller (spectrum manager), based on the spectrum sensing information, allocates the resources for efficient utilization of the available spectrum. One major role of the central controller is to prevent overlapped spectrum sharing between the secondary users [7] [9] [10].

B. Dynamic Spectrum Access

Dynamic spectrum access (DSA) is defined as real-time spectrum management in response to the time varying radio environment − e.g., change of location, addition or removal of some primary users, available channels, interference constraints etc [7] [10]. There are three DSA models in the literature, namely, exclusive-use model, common-use model and shared-use model [10]. Fig. 2.1 shows a hierarchal overview of DSA.

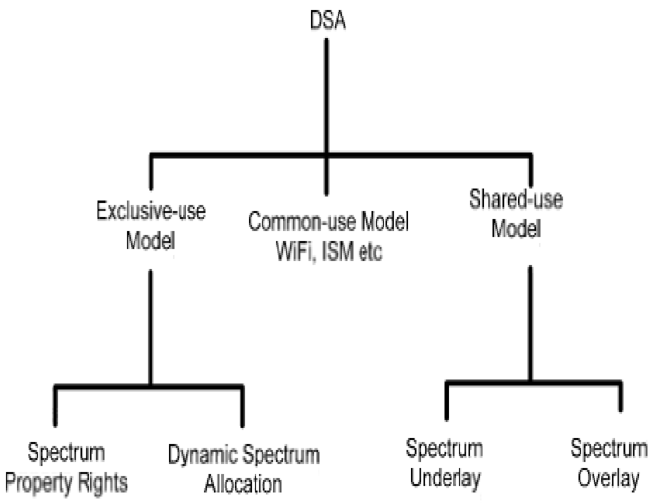

Fig. 2.1 Dynamic spectrum access strategies

The exclusive-use model has two approaches, spectrum property rights and dynamic spectrum allocation. In spectrum property rights, owner of the spectrum can sell and trade spectrum; and is free to choose the technology of interest. Dynamic spectrum allocation improves spectrum efficiency by exploiting the spatial and temporal traffic statistics of different services [10]. The European Union funded DRIVE (Dynamic Radio for IP Services in Vehicular Environments) project is a classical example of dynamic spectrum allocation [14]. It uses cellular (e.g., GSM, GPRS, and UMTS) and broadcast technologies (e.g., Digital Video Broadcast Terrestrial, Digital Audio Broadcast) to enable spectrum efficient vehicular multimedia services.

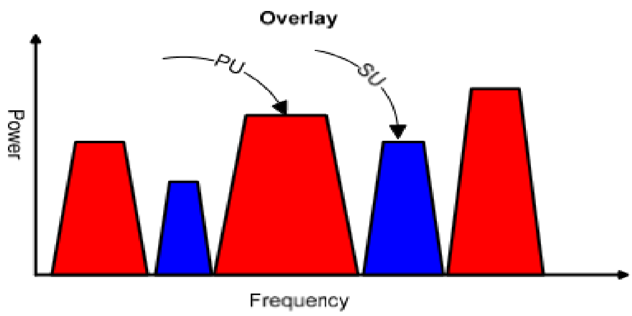

Fig. 2.2 Overlay spectrum access

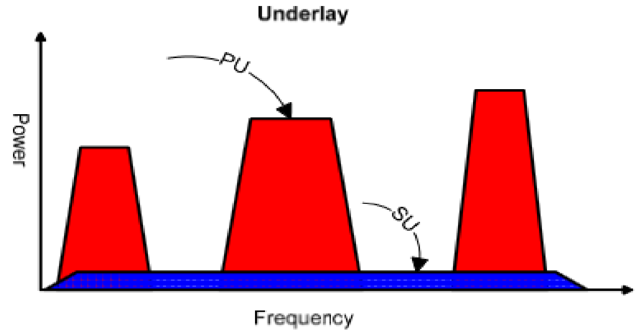

Fig. 2.3 Underlay spectrum access

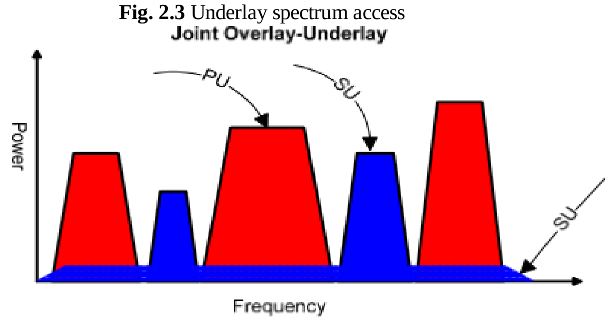

Fig. 2.4 Joint overlay and underlay spectrum access

The common-use model is an open sharing regime in which spectrum is accessible to all users. The ISM (industrial, scientific and medical) band and WI- FI are examples of the commons-use model. Spectrum underlay and overlay approaches are used in the shared-use model [9] [10]. Spectrum overlay or opportunistic spectrum access is shown in Fig. 2.2. In spectrum overlay, the secondary users first sense the spectrum and find the location of a spectrum hole (vacant frequency band). After locating the vacant frequency bands, the secondary users transmit in these frequency bands. In spectrum underlay technique, the secondary users can transmit on the frequency bands used by the primary users as long as they do not cause unacceptable interference for the primary users. This approach does not require secondary users to perform spectrum sensing, however the interference caused by the secondary user's transmission must not exceed the interference threshold. Fig. 2.3 shows the spectrum underlay model.

In [15], a joint spectrum overlay and underlay method is proposed for better spectrum utilization. An illustration of joint spectrum overlay and underlay is shown in Fig. 2.4. In joint spectrum overlay and underlay approach, the secondary users with the help of spectrum sensing first try to find a spectrum hole. If there is a spectrum hole then the secondary users can use the spectrum overlay technique. If there is no spectrum hole then the secondary users will use spectrum underlay technique.

C. Cooperative Communication

We now provide a brief background of cooperative communications. Recently the idea of cooperative communication has gained much attention. The cooperative communications exploit the broadcast nature of wireless channels. The basic idea is that the relay nodes can assist the transmissions of the source node by relaying a replica of the transmission of the source node that in turn exploits the inherent spatial diversities. Recent research in wireless communication systems shows that relaying techniques can offer significant benefits in the throughput enhancement, and range extension [1]. A number of relaying schemes e.g., amplify-and-forward (AF), decode and forward (DF), incremental relaying etc. for improving the performance of the wireless networks are in the literature e.g., [1], [16]. In a simple AF relaying scheme, a relay amplifies the received signal and forwards it to the destination. In decode and forward relaying scheme, a relay first decodes the received signal and then transmits the re-encoded signal to the destination. Table 1.2 shows a simple cooperative communication protocol. In this protocol, conveyance of each symbol from the source to the destination takes place in two phases (two time slots). In the first phase, the source transmits its data symbol, and the destination and the relay(s) receive the signal carrying the symbol. In the second phase, the relay(s) forwards the data to the destination.

Recent research on cooperative relaying has shown that half-duplex two- way relaying is spectrally more efficient [2] than the conventional half-duplex one- way, [16], relaying. In two-way relaying, a pair of users exchanges information with each other using a relay using two time slots. The key idea is that a user can cancel the interference (generated by its own transmission) from the signal it receives from the relay to recover the transmission of other terminals. Table 1.3 illustrates the two-way relaying.

Half-duplex protocols for two-way relaying using multiple relays have been discussed in [17] and [18]. In this work, we study the power allocation problem for different types of two-way relaying protocols. In one of the protocols, which we will refer to as orthogonal amplify-and-forward (OAF) relaying, the transmissions of the relays are separated in time by allocating each relay a different time-slot band. In the other relaying protocol, which we will refer to as shared-band amplify-and-forward (SAF) relaying, the relays share the same medium for their transmissions. We study the problem of jointly allocating power to the users and the relays for both OAF and SAF relaying protocols. Tables 1.4 and 1.5 show OAF and SAF bidirectional relaying protocols.

Recently, the idea of two-way relaying has been extended to the case of multiple users sharing a single relay that is referred to as multi-way relaying [8]. In this thesis, we consider multi-way relaying where relay performs amplify and forward relaying. In this relaying scheme, in the first time-slot, the users broadcast their data and in the second time-slot, the relay broadcasts the amplified data. The capacity and achievable rates for different relaying techniques (amplify-and-forward (AF), decode-and-forward and compress-and- forward) for multi-way relay channel are discussed in [3]. Table 1.6 presents the multi-way relaying communication protocol.

Time T1	Time T2
S → D, S → R	
	R → D

Table 1.2 Half-Duplex One-Way Relaying

Time T1	Time T2
S1,S2 → R	
	R → S1,S2

Table 1.3 Half-Duplex Two-Way Relaying

Time T1	Time T2	Time T3	Time T4	…	Time TL+1
S1, S2 (R1, R2,.., RL)	R1 → (S1, S2)	R2 → (S1, S2)	R3 → (S1, S2)	…	RL → (S1, S2)

Table 1.4 OAF Two-Way Relaying

Time T1	Time T2
S1,S2 → (R1,R2,…,RL)	
	(R1,R2,..,RL) → S1, S2

Table 1.5 SAF Two-Way Relaying

Time T1	Time T2
(S1, S2...,SK) → R	
	R → (S1, S2...,SK)

Table 1.6 Multi-Way Relaying

III. OBJECTIVES

The main objective of this thesis is to determine power allocation in wireless relay networks. This thesis discusses three problems: 1) Power allocation in OAF relay networks, 2) Power allocation in SAF relay networks and 3) Power allocation in multi-way relay networks. In all three problems, we examine the effect of different system parameters (e.g. maximum transmit power interference threshold level, the number of primary users, the number of secondary users, relay power levels, etc.) on the performance of the proposed algorithms.

A. Power allocation in OAF relay networks

In this work, we study a cognitive radio network (comprising multiple primary users) in which a pair of sources communicates with each other through multiple relays that employ two-way amplify-and- forward relaying. The relays use orthogonal channels to transmit their data. We formulate optimization problems to adequately decide the transmission powers of the nodes in such networks. We consider two optimization problems. In one problem, we consider maximizing the minimum among the two sources' capacities. In the other problem, we consider maximizing the sum capacity of the system. Our formulated optimization problems turn out to be non-convex and non-linear.

For theoretical interest in dealing with these non-convex optimization problems for deciding the power levels, we show in this work that these optimization problems have a set of properties that guarantees ε-convergence if the monotonic optimization techniques are used. Then, we apply the monotonic optimization [19], [20] algorithm to obtain the optimal solution of the proposed non-linear non-convex programming problems. Although the monotonic optimization algorithm can guarantee convergence to a solution that has a performance arbitrarily close (within an arbitrary number ε) to the optimal performance, our experimentation with the monotonic optimization applied to this relay power allocation problem shows rather slow convergence and heavy computational load. Therefore, we propose a low-complexity heuristics, which we name as Greedy Power Allocation with Max-Min Fairness (GPAMF) and Greedy Power Allocation with Sum Capacity

Maximization (GPASM). The simulation results show that the proposed heuristics perform well in comparison with the respective optimal solutions and have much lower computational complexity than the monotonic optimization algorithm.

B. Power allocation in SAF relay networks

In this work, we consider a cognitive radio network (comprising multiple primary users) in which a pair of sources communicates with each other through multiple relays that employ two-way amplify-and-forward relaying. The relays employ SAF relaying, i.e., in the first slot the users broadcast their data and in the second slot, the relays simply re-scale and re-transmit the received signal.

We study the problem of allocating powers to the users and relays such that the minimum among the users' SNRs is maximized subject to the constraints on the transmit power of the nodes. The formulated optimization problem is non- convex non-linear program and we do not see a special structure that could guarantee the quality of a solution. We observe that we can transform the problem into an equivalent problem (although still a non-convex non-linear program) which exhibit a special property. In the transformed problems, we observe that the objective function and the constraints are increasing function of each optimization variable when other variables are fixed. This property enables us to determine the global optimal solution to our optimization problems by applying the concepts of monotonic optimization algorithm [19]. Monotonic optimization algorithm guarantees convergence to a solution that has a performance arbitrarily close (within an arbitrary number ε) to the optimal performance. However, the application of monotonic optimization techniques to solve the optimization problem requires significant computations. Therefore, we propose a low-complexity heuristic. We perform simulations to examine the quality of the solution obtained from the proposed heuristic and benchmark its performance using the optimal solution obtained by using monotonic optimization techniques.

C. Power allocation in Multi-Way relay networks

In this work, we consider a multi-way relay channel comprising multiple users and a single relay. We assume that the relay terminal uses AF relaying. For such systems, we study the problem of allocating power to the users and the relay terminal such that the minimum among the users' transmission rates is maximized subject to the constraints on the transmission power of the nodes. The formulated optimization problem is a non-convex non-linear program and does not have a structure to guarantee the quality of a solution. We observe that we can transform the problem into another equivalent problem (although still a non-convex non-linear program) which could be solved to global optimality by applying the concepts of monotonic optimization algorithm [19]..

IV. CONCLUSION

In this paper we considered a multi-way relay channel comprising multiple users and a relay where the users wish to exchange information among them with the help of the relay terminal. The relay used amplify-and-forward (AF) relaying. We formulated the optimization problem of allocating power to the users and the relay such that the minimum among the user's rate is maximized. Then, we presented a method of transforming the problem to a new formulation so that a ε- optimal algorithm can be designed. The formulated problem, although still non- convex, can be solved by the monotonic optimization.

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