Chapter 2
Cognitive Interference Alignment for Spectral Coexistence

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Abstract Interference Alignment (IA) has been widely recognized as a promising interference mitigation technique since it can achieve the optimal degrees of freedom in certain interference limited channels. In the context of Cognitive Radio (CR) networks, this technique allows the coexistence of two heterogeneous wireless systems in an underlay cognitive mode. The main concept behind this technique is the alignment of the interference on a signal subspace in such a way that it can be filtered out at the non-intended receiver by sacrificing some signal dimensions. This chapter starts with an overview of IA principle, Degree of Freedom (DoF) concept, and the classification of existing IA techniques. Furthermore, this chapter includes a discussion about IA applications in CR networks. Moreover, a generic system model is presented for allowing the coexistence of two heterogeneous networks using IA approach while relevant precoding and filtering processes are described. In addition, two important practical applications of the IA technique are presented along with the numerical results for underlay spectral coexistence of (i) femtocell-macrocell systems, and (ii) monobeam-multibeam satellite systems. More specifically, an uplink IA scheme is investigated in order to mitigate the interference of femtocell User Terminals (UTs) towards the macrocell Base Station (BS) in the spatial domain and the interference of multibeam satellite terminals towards the monobeam satellite in the frequency domain.

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2.1 Introduction

The demand for the broadband wireless spectrum is increasing due to rapidly increasing number of broadband and multimedia wireless users and applications. Due to the limited and expensive frequency resources, Cognitive Radio (CR) communication can be an efficient technique to enhance the spectrum efficiency since it allows the coexistence of primary and secondary wireless networks within the same spectrum. Wireless networks may coexist within the same spectrum band in different ways such as two terrestrial networks, two satellite networks or satellite-terrestrial networks. Due to the recent advancements in terrestrial cellular technology and multibeam satellite technology, denser deployments of cells/beams have become possible for providing higher capacity and network availability. In the context of terrestrial systems, small cell systems such as femtocells have received important attention due to higher cellular capacity and energy efficiency harnessed by switching unused femtocells in a sleep mode [3]. Furthermore, femtocells can provide better user experience with lower capital and operational costs compared to other techniques for indoor coverage. Similarly, in the satellite paradigm, multiple beams can be employed instead of a single global beam in order to enhance the capacity [12]. However, current network configurations use large cell systems and the deployment of new small cell systems need additional bandwidth which is scarce and expensive to acquire. In this context, dense small cell systems have to coexist with the traditional large cell systems to optimally utilize the existing spectrum.

Interference is an inevitable phenomenon in wireless communication systems when multiple uncoordinated links share a common wireless channel. The coexistence of different wireless networks in the same spectrum band can be modeled as CR networks with interference channels between primary and secondary systems. The operation of the primary network usually follows a well established standard and should not be degraded while the secondary network should employ some advanced transmission and coding techniques in order to exploit the underutilized dimensions in the frequency, time and space domains. Depending on the strength of the interference between wireless networks, different interference management approaches can be applied. If the interference is weaker than the noise floor, the interference signal can be treated as noise and the single user encoding/decoding mechanisms can be applied. Because of its simplicity and ease of implementation, this approach is widely used in practice, but does not achieve interference-free capacity even for the simple case of a Broadcast Channel (BC) [71]. If the interference level is strong in comparison to the noise floor, it is possible to decode the interference and then subtract it from the received signal. This method is less common in practice due to its complexity and security issues. However, when the strength of the interference is comparable to the desired signal, treating as noise is not an option because of interference constraints involved while decoding and canceling requires complex primary receivers. In this case, one approach is to orthogonalize channels so that transmitted signals are chosen to be non-overlapping in the time, frequency or space domain, leading to Time Division Multiple Access

(TDMA), Frequency Division Multiple Access (FDMA) or Space Division Multiple Access (SDMA) respectively. Furthermore, in multiuser interference networks, applying the above techniques is problematic since the aggregate interference may be stronger than the noise floor in many cases and decoding may also be complex due to involvement of several interfering users. Although the orthogonalization approach effectively eliminates multiuser interference in wireless networks, it may lead to underutilization of communication resources and it also does not achieve the capacity of interference channels [51]. In this context, Interference Alignment (IA) has received important attention as an interference mitigation tool in interference-limited wireless systems such as cellular wireless networks, CR systems and ad-hoc networks.

The remainder of this chapter is structured as follows: Sect. 2.2 introduces the fundamentals of the IA technique including Degrees of freedom (DoF) concept, basic IA principle and the classification of IA techniques. Section 2.3 includes the current state of art related to the application of IA in CR networks. Section 2.4 includes the generic system model for spectrum coexistence scenario in which IA technique can be applied and further describes the mechanism for IA and filtering process. Section 2.5 provides the application of different IA approaches for the following two practical scenarios including numerical results: (i) femtocell-macrocell coexistence scenario, and (ii) monobeam-multibeam satellite coexistence. Section 2.6 presents the challenges of IA technique from practical perspectives and further includes future research directions. Section 2.7 summarizes the chapter.

2.1.1 Notation

Throughout this chapter, boldface upper and lower case letters are used to denote matrices and vectors respectively, $\mathbb{E}[\cdot]$ denotes expectation, $(\cdot)^\dagger$ denotes the conjugate transpose matrix, $(\cdot)^T$ denotes the transpose matrix, $O(\cdot)$ denotes the order, $(z)^+$ denotes $\max(0, z)$, and $\mathbf{0}$ represents a zero matrix

2.2 Interference Alignment (IA) Fundamentals

In wireless interference networks, only a subset of the transmitted symbols are desired by a particular receiver. The remaining symbols, which carry information for other receivers, are undesired at that particular receiver creating interference to the desired signal. In this context, IA can be used as an interference mitigation tool which aligns interference in the space, time or frequency domain using precoding techniques. The main principle behind IA is the alignment of the interference on a signal subspace in such a way that it can be easily filtered out at the non-intended receiver by sacrificing some signal dimensions. In other words, signals transmitted by all users can be designed in such a way that the interfering signals fall into a reduced dimensional subspace at each receiver. Each receiver can then apply an interference removal filter to project the desired signal onto the interference free subspace. Due to this approach, the number of interference-free signalling dimensions of the network are substantially increased [27]. In Multiple Input Multiple Output (MIMO) networks, IA can be applied by using the spatial dimension offered by multiple antennas for alignment while in multicarrier systems, interference can be aligned along the carrier dimension.

2.2.1 Degrees of Freedom (DoF)

The DoF is an important metric used for capacity approximation in wireless networks literature. It may be interpreted as the number of resolvable signal space dimensions and is a way of measuring the spatial multiplexing gain provided by MIMO systems at high Signal to Noise Ratios (SNRs). It can also be defined as the number of signaling dimensions, each dimension corresponding to one interference-free Additive White Gaussian Noise (AWGN) channel with Signal to Noise Ratio (SNR) that increases proportionally with the total transmit power P as $P \to \infty$ [27]. The DoF also corresponds to the multiplexing gain, bandwidth, capacity pre-log factor, or the number of signaling dimensions. Let $R(P)$ denotes the sum capacity, then the DoF metric, let us denote by η, is given by

$$\eta = \lim_{P \to \infty} \frac{R(P)}{\log(P)}. \tag{2.1}$$

The above expression can be equivalently written as: $R(P) = \eta \log(P) + O(\log(P))$, where the term $O(\log(P))$ is some function $f(P)$ which satisfies the following relation [27]

$$\lim_{P \to \infty} \frac{f(P)}{\log(P)} = 0. \tag{2.2}$$

For example, a point to point MIMO channel with M transmit and N receive antennas has $\min(M, N)$ DoF, whereas it's Single Input Single Output (SISO) counterpart has only 1 DoF [65].

The DoF regions are characterized for several wireless channels such as MIMO BC, interference channels (ICs), including X and multihop ICs, and the CR channels [68]. The DoF metric has been extensively used for interference mitigation and alignment objectives in various wireless networks such as interference mitigation in multicell networks [10, 31], interference mitigation in two-cell MIMO interfering BCs [63], IA in CR networks [14, 34, 57]. The main limitation of the DoF metric is that it does not provide much insight to optimally manage interference when all signals are not comparable, since it forces all channels to be equally strong. In this case, another metric, called Generalized DoF (GDoF), can be used [4]. This metric can preserve the diversity of signal strengths by fixing the ratios of different signal powers when all SNRs approach infinity. Let α denote the ratio of the cross channel strength to the direct channel strength in dB scale and $R(P,\alpha)$ denote the sum-capacity. Then the total GDoF metric, $\eta(\alpha)$ can be defined as [27]:

$$\eta(\alpha) = \lim_{P\to\infty} \frac{R(P,\alpha)}{\log(P)}. \tag{2.3}$$

It can be noted that the GDoF metric corresponds to the DoF metric when $\alpha = 1$. This metric has been successfully used in [4, 18] to approximate the capacity of two user interference channel and in [46] for multiple antenna scenarios considering two user MIMO interference channel.

2.2.2 IA Principle

The IA technique allows many interfering users to communicate simultaneously over a small number of signaling dimensions i.e., number of antennas or carriers. This is achieved by aligning the space spanned by the interference at each receiver within a small number of dimensions and keeping the desired signals distinguishable from interference so that they can be projected into null space of the interference and desired signal can be recovered from the received signal. The disadvantage of the IA approach is that filtering at the non-intended receiver removes the signal energy in the interference subspace. Let us consider an interference network with K transmitters, each trying to send one information symbol. To resolve the 1 symbol desired by a particular receiver, K signalling dimensions are generally required [27]. If there are K number of receivers, each with access to a different set of K linear equations formed by its linear channel to the transmitters and interested in a different symbol, a total number of K signalling dimensions will be sufficient to recover the desired symbol by all the K receivers. In this case, the total signalling dimensions are shared among the K users so that each user can communicate using $1/K$ fraction of it like a cake-cutting bandwidth allocation. If all the available receiving dimensions are spanned by interference beams, the desired signal will lie within the interference space as well and can not be resolved. However, if the signals can be designed in such a way that the interference beams can be consolidated into a smaller subspace i.e., they do not span the entire available signal space at the receiver, and the desired signal beam can avoid falling into the interference space, then the receiver becomes able to recover its desired symbol. The advantage of this mitigation approach is that this alignment does not affect the randomness of the signals and the available dimensions with respect to the intended receiver. The fundamental assumptions which make IA feasible are that there are multiple available dimensions (space, frequency, time or code) and that the transmitter is aware of the Channel State Information (CSI) towards the non-intended receiver.

The relativity of alignment is an important aspect for enabling IA in interference wireless networks [5]. It implies that when there are multiple non-intended receivers, the alignment of signals in these receivers is different i.e., the set of input-output equations observed in each receiver is different from those observed in other receivers. Since the signals do not align into the desirable patterns naturally, the most important challenge for IA techniques is the design of signal vectors to fulfill the desired alignment conditions, which are explained later in Sect. 2.3 for different IA techniques. In the context of multiple non-intended receivers, applying IA is not straightforward since the alignment for one receiver in general does not ensure alignment at other receivers as well.

For the Gaussian interference channel with K interfering transmitter-receiver pairs with each transmit and receive node having M antennas each, and with random, time-varying channel coefficients drawn from a continuous distribution, the sum-capacity of the network is characterized as [5]:

$$R(P) = \frac{KM}{2}\log(P) + O(\log(P)). \tag{2.4}$$

In this case, capacity per transmit-receive pair, i.e., for one user, becomes $\frac{M}{2}\log(P) + O(\log(P))$, where P is the total transmit power of all the transmitters in the network when the noise power is normalized to unity. The term $O(\log(P))$ becomes negligible as compared to $\log(P)$ at high SNRs and the accuracy of the capacity approximation approaches 100 %. Based on the results obtained in [5], it can be deduced that every user in a wireless interference network is (simultaneously and almost surely) able to achieve approximately one half of the interference-free capacity. From the sum-rate perspective, with K user pairs, an IA strategy achieves the sum throughput on the order of $K/2$ interference-free channels. More specifically, each user can effectively get half the system capacity. Thus in contrast to conventional interference channels, there is increase in the sum rate with the number of active user pairs. To illustrate the IA principle, Fig. 2.1 presents the spectral coexistence scenario of a primary and a secondary cellular networks. The secondary transmitters apply precoding using a predefined or coordinated alignment vector before transmitting so that the interfering signals are all aligned at the primary receiver at a certain direction. Then the received signal at the primary receiver is filtered out by using suitably designed filter so that the interference is filtered out, only leaving the desired signal at the output. The detailed description on this alignment and filtering process is presented in Sect. 2.4.

The main drawback of the IA technique from practical point of view is that it requires the global or local CSI knowledge depending on the applied techniques. The CSI for IA operation can be obtained basically by the following two methods [17].

1. **CSI through Reciprocity**: In Time Division Duplex (TDD) based systems, propagation in both directions can be considered to be identical and the channels are said to be reciprocal. Reciprocity enables the IA by allowing transmitters to

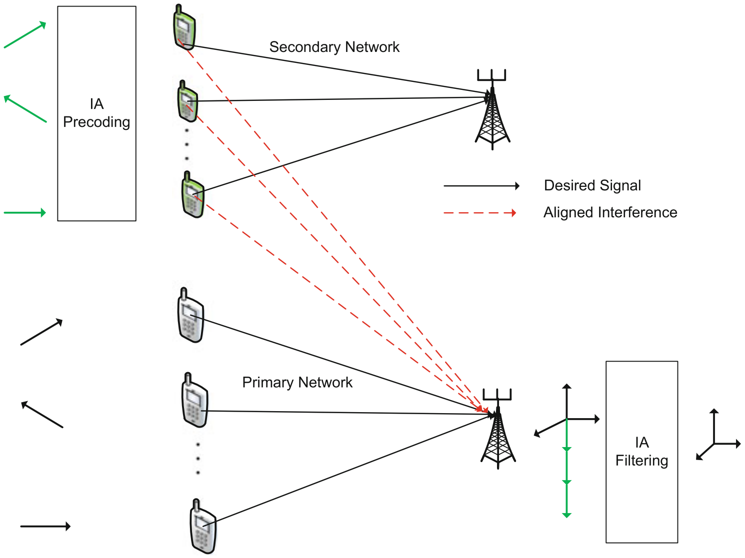


Fig. 2.1 Illustration of IA principle in a cellular network

predict the strength of the interference they cause by observing the interference they receive. The general framework for reciprocity consists of forward link training and reverse link training until the convergence occurs and then the data transmission phase gets started.

2. **CSI through Feedback**: In this approach, a transmitter first sends a training sequence and based on this training sequence, the receiver estimates the forward channel. Subsequently, the receiver feeds back this estimated channel information, potentially after training the reverse link. After feedback, the transmitter has the information needed to design an IA precoder. The disadvantage of this method is that feedback process introduces distortion to the CSI at the transmitter and may create a non-negligible overhead penalty.

2.2.3 Classification of IA Techniques

The IA technique was firstly proposed in [6] and channel capacity as well as DoFs for the interference channel have been analyzed. This technique has been shown to achieve the DoFs for a range of interference channels [5, 7, 28]. Finding out the exact number of needed dimensions and the precoding vectors to achieve IA is a cumbersome task but a number of approaches have been presented in the literature for this purpose [21, 66, 75]. The IA technique was also investigated in the context of cellular networks, showing that it can effectively suppress cochannel interference [9, 15, 64, 66]. More specifically, the downlink of orthogonal frequency division multiple access (OFDMA) cellular network with clustered multicell processing is considered in [15], where IA is employed to suppress intracluster interference while intercluster interference has to be tolerated as noise. In addition, authors in [64] consider the uplink of a limited-size cellular system without Multicell Joint Decoding (MJD), showing that the interference-free DoFs can be achieved as the number of User Terminals (UTs) grows large. In the same context, authors in [10] employ IA as an uplink interference mitigation technique amongst cooperating Base Station (BS) clusters for Rayleigh channels. In the context of small cells, the study in [41] extends [10] by assuming clusters of small cells which dictate the use of a Rician fading channel.

The IA technique has also been investigated in multicarrier systems in different settings [15, 19, 38, 62]. A projection based IA technique including the concepts of signal alignment and channel alignment has been investigated in [19]. The IA technique for an interference network with the multicarrier transmission over parallel sub-channels has been tackled in [62]. The signal alignment for multicarrier code division multiple access (MC-CDMA) in two way relay systems has been studied in [38]. Despite various literature about IA in terrestrial cellular networks, only a few studies have been reported about IA in satellite literature. The feasibility of implementing subspace interference alignment (SIA) in a multibeam satellite system has been studied in [30] and it has been concluded that the SIA applied in the frequency domain is advantageous for multibeam satellites.

IA can be broadly classified into two categories: signal level alignment and signal space alignment [37]. The signal level alignment leads to the tractability to DoF characterization while the signal scale alignment provides an attractive way to realize IA in practice. The signal space can be generated in several ways such as by concatenating time symbols, frequency bins, or space domain. Several IA techniques have been reported in the literature based on the availability of CSI knowledge at the transmitter (CSIT), number of signal dimensions used for aligning the interference, and interference removal methods applied at the desired receiver. Existing IA techniques are listed in Table 2.1 along with the corresponding references and briefly described in the following paragraphs.

Linear Interference Alignment: Linear IA is the simplest form of IA in which the alignment of signal spaces is done based on linear precoding (beamforming) schemes. This IA scheme operates within the spatial dimensions provided by multiple antennas at the transmit and receive nodes. Since beamforming schemes are common in the existing point to point MIMO, BC and multiple access networks, linear IA seems to be the most easily accessible form of IA from practical point of view. A linear IA problem becomes a proper or improper based on whether or not the number of equations exceeds the number of variables [75]. The proper systems are likely to be practically feasible and improper systems are likely to be infeasible. Let us consider K user MIMO interference setting with M number of antennas in each transmitter and N number of antennas in each receiver. According [75], the $(M \times N, d)^K$ linear IA problem, d being the number of independent streams, is proper if and only if the following condition is satisfied: $d \leq \frac{M+N}{K+1}$.

Table 2.1 Lists of IA techniques

IA	CSIT	Signal dimensions	Interference removal	References
Linear IA	Perfect/delayed	Single	Filtering	[37, 51, 75]
Subspace IA	Perfect	Multi	Filtering	[37, 64, 70]
Distributed IA	Local	Single	Filtering	[21,22,52,53]
Blind IA	No	Single	Filtering	[23, 26]
Ergodic IA	Perfect/delayed	Single	Filtering	[33, 42]
Asymptotic IA	Perfect	Single	Filtering	[23]
Retrospective IA	Delayed	Single	Filtering	[33, 35, 39]
Lattice alignment	Perfect	Single	Decoding	[4, 44]
Symbol extensions	Multiple channel uses	Fractional	Filtering	[28, 72]
IA and cancelation	Perfect	Single/multi	Filtering and decoding	[73, 74]
Opportunistic IA	Perfect	Single/multi	Filtering	[43, 47]
Asymmetric complex signalling	Complex	Two	Filtering	[8, 29]

Subspace IA: In this scheme, the interferences are aligned to multidimensional subspace instead of a single dimension. In the context of cellular networks, IA scheme provides advantage due to multiuser gain and aligning interferences becomes challenging in the three cell case since there exist multiple non-intended receivers [64]. The IA for one receiver does not guarantee the alignment in the other receivers as well. In fact, this problem arises due to the strict constraint that interferences are mainly aligned into a single dimension. This can be addressed by relaxing the constraints and aligning interferences into multidimensional subspace instead of a single dimension, called as subspace IA. The main concept behind the subspace IA is to align K interfering vectors into $\sqrt{K} + 1$ dimensions (instead of one dimension) to enable simultaneous alignments at the multiple receivers. Since $\sqrt{K}$ becomes negligible compared to K as K gets large, the interference-free DoF can be approached. The interference-free DoF can be achieved as the number of mobiles in each cell i.e., K increases in the context of cellular networks while using the subspace IA. For the G-cell case with K users in each cell, the achievable DoF per cell has been shown to be [64]

$$\frac{K}{(\sqrt[G-1]{K} + 1)^{G-1}} \rightarrow 1 \text{ as } K \rightarrow \infty. \tag{2.5}$$

Distributed IA: Distributed IA is based on the local channel knowledge instead of global channel knowledge. Several iterative algorithms in the literature have focused on finding the alignment solutions numerically. The motivation for an iterative approach in [22] is to achieve IA with only local channel knowledge, by exploiting the two way nature of communication and the reciprocal nature of the physical propagation medium. The alternating minimization approach proposed in [49] uses similar distributed IA but does not explicitly assume channel reciprocity. An alternative approach based on weighted minimum mean square error (MMSE) beamforming proposed in [52] compares favorably to the max-Signal to Interference and Noise Ratio (SINR) algorithm and can also provide unequal priorities for the users' rates.

Let us consider a cellular system with B BSs equipped with N antennas and each BS exclusively provides wireless service to K users each equipped with M antennas. The DoFs of a $((B, N) \times (K, 1))$ cellular system with $B > 1$ is given by [53] $d = BK + \frac{BKN}{K+N}$ if N/K is an integer.

Blind IA: Most of the IA results are based on the assumption of perfect, and sometimes, global channel state information at the transmitters. It has been noted that the DoFs of many networks collapse entirely to what is achievable simply by orthogonal TDD among users in the absence of channel knowledge. In this context, there is still possibility of aligning interference based on the knowledge of the distinct autocorrelation properties of the channels observed by different receivers without knowing exact channel coefficients [26]. This is referred as a blind IA technique.

Ergodic IA: In ergodic settings, the channel states can be partitioned into complimentary pairings for a broad class of channel distributions over which the interference can be aligned so that each user is able to achieve (slightly more than) half of his interference-free ergodic capacity at any SNR [42]. The main concept behind this lies on the pairing of channels i.e., matching almost every channel matrix with its complement. Ergodic alignment achieves the capacity when the channel is in a bottleneck state i.e., the number of transmit-receive pairs approaches infinity. In this scheme, each user can achieve at least half of its interference-free capacity at any SNR [42], i.e., $R_k = \frac{1}{2}\mathbb{E}[\log(1 + 2|h_{kk}|^2 P_k)] > \frac{1}{2} R_k^{\text{free}}$, where P_k denotes the transmit power of the kth user, and R_k^{free} denotes the interference-free capacity.

Asymptotic IA: Ergodic IA is an opportunistic scheme that exploits the existence of complementary channel states in equal proportions to achieve the linear IA. Although this assumption applies to a broad variety of channel distributions including Rayleigh fading models, it is not universally applicable since the arbitrary channel distributions, or even standard ones such as Rician fading, do not satisfy the symmetric phase assumptions made by ergodic IA [7]. Although this scheme is of theoretical in nature, it has many advantages such as flexibility of large number of alignment constraints, applicable to both linear and nonlinear forms and for a variety of scenarios ranging from K-user ICs, X networks, cellular networks, compound BC channels, and network coding applications.

Retrospective IA: Retrospective IA techniques refer to the IA schemes that exploit only delayed CSIT. The delayed CSIT is generally assumed to be independent of the current channel state. However, perfect knowledge of channel states is available at the transmitter with some delay. For retrospective IA, the channels can (but do not have to) be independent and identically distributed (i.i.d.) isotropic [35]. In the absence of the delayed CSIT, i.i.d. isotropic fading channels would lose all signal multiplexing benefits and only have 1 DoF. The result obtained in [35] in the context of a vector BC channel is that CSIT is helpful even if it is outdated and it can have a significant impact since it is capable of increasing the DoF. The delayed feedback can be basically obtained in the following three settings: (i) delayed CSIT: only the past channel states are fed back and not the output signals, (ii) delayed output feedback: only the past received signals are fed back and not the channel states, and (iii) delayed Shannon feedback: the past received signals as well as channel states are fed back. This is the strongest delayed feedback setting, i.e., it can be weakened to obtain either delayed CSIT or the delayed output feedback model by discarding some of the feedback information.

Lattice alignment: Lattice alignment refers to the use of lattice codes in an interference network with the lattices scaled in such a manner that the undesired signals at an interfered receiver arrive on the same lattice, and the desired signal stands apart, i.e., does not occupy the same lattice [4]. The main concept behind this IA scheme is that since the sum of lattice points (codewords) is also a lattice point (a valid codeword), it may be possible to decode the sum of lattice points even if the individual latices by themselves are not decodable. This scheme is mainly applicable for constant channels. Reference [44] considers lattice IA approach for a static real K-user interference channel and derives an achievable rate region for such channels which is valid for finite SNR. For such channels, many results demonstrate that the number of DoFs is very sensitive to slight variations in the direct channel gains.

IA based on Symbol Extensions: Spatial beamforming based linear IA techniques basically operate in the spatial dimensions provided by multiple antennas at the transmit and receive nodes, and divide these spatial dimensions into separable subspaces to be occupied by interference and desired signals at each receiver. In the case of insufficient number of antennas, spatial IA schemes do not find a enough vector space to operate. Furthermore, since the number of beams must be an integer, purely spatial beamforming based IA schemes can only achieve an integral number of signal dimensions per message per channel use. In this case, beamforming across multiple channel uses can be an alternative option to increase the total signal space. For example, the size of the total signal space at each node is increased three times using three channel uses. The concept behind the symbolic extensions is to perform beamforming across multiple channel uses. This technique has been successfully applied for X channel [28] and compound MIMO BC channel [72]. The disadvantage of this approach is that symbol extensions over constant channels do not automatically provide the diversity of linear transformations that is needed for linear IA.

Asymmetric Complex Signalling: Due to lack of rotations in the constant channels while using symbol extensions, the alignment of vector spaces is identical at each receiver thus making IA infeasible. To overcome the disadvantage of symbol extensions in constant channels, the concept of asymmetric complex signalling has been introduced in [29]. Since we usually deal with the complex numbers for channel coefficients, transmitted and received symbols as well as the noise, phase rotations can be exploited to find distinct rotations at each receiver. This can be realized as rotations in two dimensional real-imaginary plane and this is the main concept behind asymmetric complex signalling method [8, 29].

Interference Alignment and Cancelation: The combination of IA and cancelation (IAC) may be applied to the scenarios where neither IA nor cancelation applies alone. It is shown in [74] that the IAC almost doubles the multiplexing gain (i.e., number of concurrent transmissions) of flat fading interference-limited MIMO channels. In the IAC scheme proposed in [73], the messages are first transformed into asymmetric input with structured coding, and then the dimensions occupied by interference on each receiver are minimized with the help of an appropriate alignment and cancelation technique.

Besides the above techniques, the combined alignment techniques such as signal and channel alignment [19], joint signal and interference alignment [16], joint interference and phase alignment [50] have also been investigated in the literature.

2.3 IA in Cognitive Radio Networks

The IA technique can be classified as an underlay CR technique [20] since it deals with interference mitigation towards the primary system in spectral coexistence scenarios. In the context of coexistence of macrocell and the small cells, authors in [11] have applied the IA technique in order to mitigate the interference from small cells towards the macrocell BS. Similarly, the authors in [40] proposed Vandermonde-subspace frequency division multiplexing for the downlink in order to null out the interference of small cells towards primary macro users. In the coexistence of macro/femto networks, authors in [25] have studied a joint opportunistic interference avoidance scheme with Gale-Shapley spectrum sharing based on the interweave paradigm in order to mitigate both tier interferences. In the proposed scheme, femtocells opportunistically communicate over available spectrum with minimal interference to macrocells while the femtocells are assigned orthogonal spectrum resources to avoid intratier interference. Furthermore, authors in [57] study the application of IA technique exploiting the carrier domain for the coexistence of multibeam and monobeam satellites in order to mitigate the interference of multibeam satellite terminals towards the monobeam satellite. Considering the DoF perspective, the Primary User (PU) does not fully utilize the DOF it can achieve and the primary radio resources are underutilized. In other words, there are free DoFs (DOF holes) in the primary radio resources [14]. As an example, a PU with 1 transmit and 1 receive antenna, who transmits 2 symbols every 3 time slots only utilizes $2/3$ DoF while the maximum DoF it can get is 1. So, it is possible for the SUs to access the $1/3$ DoF to improve the total DoF of the wireless system.

In the context of CR networks, IA techniques can be broadly classified into non-cooperative and cooperative. Several contributions in the literature have investigated an opportunistic IA scheme in non-cooperative scenarios. The ergodic IA can be considered as an opportunistic scheme that exploits the existence of complementary channel states in equal proportions to achieve IA [48]. The primary CR link can be modeled by a single user MIMO channel since it must operate free of any additional interference caused by secondary systems. Then, assuming perfect CSI at both transmit and receive ends, capacity can be achieved by implementing a water filling power allocation scheme over the spatial directions. It can be noted that even if the primary transmitters maximize their transmission rates, some of their spatial directions are unused due to power limitations. These unused spatial dimensions can therefore be reused by another system operating in the same frequency band in an opportunistic way. An opportunistic secondary transmitter can send its own data to its respective receiver by processing its signal in such a way that the interference produced on the primary link impairs only the unused spatial dimensions. Using the above principle, authors in [47] consider the opportunistic IA considering same number of antennas and same power budget on both primary and secondary devices while authors in [48] consider the opportunistic IA with a general framework where devices have different number of antennas. Furthermore, authors in [1] extend the contribution of [48] considering multiple SUs.

In the context of the cooperative IA technique, authors in [24] study the femto-macro coexistence scenario in order to manage the uplink interference caused by the macrocell users at the femtocell BS (FBS). By means of coordination between multiple FBS and the macrocell users, the received signals from macrocell users can be aligned in a lower dimensional subspace at the multiple FBSs simultaneously. Then the remaining DoFs are exploited to improve the performance of the femtocell users. Similarly, the contribution in [45] considers a cooperative approach to address the interference problem in femtocell networks by allowing the FBSs to perform IA cooperatively in order to reduce their mutual interference and improve the overall performance. Given a number of FBSs deployed over an existing macrocell network, a cooperative strategy is proposed in [45], where the mutual interference inside a coalition of FBSs is aligned in a subspace which is orthogonal to each desired signal. The remaining part of the network, which is non-cooperative, contributes with non-aligned interference on each of the receiver's subspaces.

Furthermore, several IA based cognitive schemes have been proposed in [2] in order to exploit the free spatial dimensions left by the PU. In these schemes, the precoding matrices of the SUs are jointly designed so that no interference is generated at the primary receiver. Furthermore, each secondary receiver does not experience any interference from the primary transmission or from the other SUs. The upper bound of the DoF for a SU (with a single transmitter and receiver) with M_1 antennas at the transmitter and N_1 antennas at the receiver operating in the presence of a PU having d_0 active streams has been found to be [14] $d_1 < \min\{(M_1 - d_0)^+, (N_1 - d_0)^+\}$. Subsequently, for the multiple SUs, each with M number of antennas, the achievable DoF has been found as $(M - d_0)^+$. This bound is the best known bound for cognitive systems without user cooperation

[14]. It indicates that each SU can asymptotically access half the DoF holes. In [14], it is shown that each cognitive user can almost get the whole DoF holes by properly designing their beamforming vectors. According to [14], the number of DoF of the secondary network is given by

$$\max_{\mathcal{D}} \sum_{i=1}^{K} d_i = K \min(\frac{1}{2}, 1 - d_0), \tag{2.6}$$

where $\mathcal{D}$ is the DoF region for the cognitive network and K is the number of SUs. Furthermore, partial and full aided IA schemes can be applied based on the cooperation benefits provided to the PUs.

Moreover, the contribution in [36] studies a trade-off between the Opportunistic Resource Allocation (ORA) and IA techniques in OFDMA based techniques. In the ORA method, the system needs to find an appropriate sub-channel for a femtocell user for which this user has a higher received power from its own BS and less interference from the macrocell transmission so that the total sum-rate is maximized. On the other hand, the IA utilizes fading fluctuations in the frequency domain to generate precoding vectors which create interference-free channels [36]. With the help of numerical results, it has been shown in [36] that the system tends to allocate more sub-channels to perform ORA and achieve the highest sum-rate in low SNR regime while more sub-channels to perform IA in high SNR regime.

2.4 Spectral Coexistence

In this section, we present a generic system model for the spectral coexistence of cognitive systems with primary licensed systems, describing the precoding as well as filtering process. We apply a linear IA technique based on precoding and filtering assuming the perfect CSI knowledge at the secondary transmitters.

2.4.1 Generic System Model

Let us consider a spectral coexistence of a primary system and a secondary system, both operating in a normal uplink mode with the primary system as a single-user uplink and the secondary system as a multiuser uplink. For example, the primary system can be a macrocell system or a monobeam satellite system and the secondary system can be a femtocell system or a multibeam satellite system, which will be described in detail in Sect. 2.5. Usually the primary system is already deployed system and the secondary system should not affect the operation of the primary systems. We consider that the Primary Transmitter (PT) has M signalling dimensions (which can be the number of antennas or carriers) and Primary Receiver

(PR), Secondary Transmitter (ST), and Secondary Receiver (SR) have $L = M + 1$ number of signalling dimensions. This means that there is a single unutilized dimension in the primary link. We consider a single PT, N number of STs and the STs are assumed to be able to cooperate and jointly decode the received signals. Furthermore, the STs are assumed to be aware of the CSI towards the PR and in practice, this knowledge can be obtained by applying the methods mentioned in Sect. 2.2.

In addition to the CSI knowledge, the STs and the PR should be aware of a predefined IA vector, let us denote by $\mathbf{v}$, to perform IA. Depending on how $\mathbf{v}$ is calculated, three different IA techniques can be considered, namely, static, uncoordinated, and coordinated. These techniques basically depend on the level of coordination between primary and secondary systems. The concept behind the applied cognitive IA is to employ precoding at the STs so that the received secondary signals at the PR are all aligned across the alignment vector $\mathbf{v}$. In this way, interference can be filtered out by sacrificing one DoF and some part of the desired received energy. However, after filtering the signal is interference free and can be easily decoded using conventional detection techniques. We mention this technique as cognitive IA since the STs have to be aware of the CSI and the vector $\mathbf{v}$ to perform the precoding. On the other hand, the PR needs only to perform filtering adapted to vector $\mathbf{v}$ and no additional awareness or intelligence is required. The received signal at the PR can be written as:

$$\mathbf{y}_1 = \mathbf{H}\mathbf{x} + \sum_{i=1}^{N} \mathbf{F}_i \mathbf{x}_i + \mathbf{z}_1, \tag{2.7}$$

where $\mathbf{y}_1$ is the $L \times 1$ received symbol vector, $\mathbf{x}$ is the $M \times 1$ transmitted symbol vector from the PT, $\mathbf{x}_i$ is the $L \times 1$ transmitted symbol vector from the ith ST and $\mathbf{z}_1$ is the receiver noise. All inputs $\mathbf{x}, \mathbf{x}_i$ are assumed to be Gaussian and obey the following sum power constraints: $\mathbb{E}[\mathbf{x}^\dagger \mathbf{x}] \leq \gamma_{ps} M$ and $\mathbb{E}[\mathbf{x}_i^\dagger \mathbf{x}_i] \leq \gamma_{ss} L$, γ_{ps} being the transmit SNR of the PT and γ_{ss} being the transmit SNR of the ST. The $L \times M$ matrix $\mathbf{H}$ represents the channel gains between the PR and the PT while the $L \times L$ matrix $\mathbf{F}_i$ represents the channel gains between the PR and ith ST.

Let's group all $\mathbf{F}_i$ into a single $L \times NL$ matrix $\mathbf{F} = [\mathbf{F}_1 \ldots \mathbf{F}_N]$ to simplify notations. The received signal at the joint processor of the SRs is

$$\mathbf{y}_2 = \sum_{i=1}^{N} \tilde{\mathbf{F}}_i \mathbf{x}_i + \tilde{\mathbf{H}}\mathbf{x} + \mathbf{z}_2, \tag{2.8}$$

where $\mathbf{y}_2$ is the $NL \times 1$ received symbol vector and $\mathbf{z}_2$ is the receiver noise. The $NL \times M$ channel matrix $\tilde{\mathbf{H}}$ represents the channel gains between all SRs and the PT while the $NL \times L$ channel matrix $\tilde{\mathbf{F}}_i$ represents the channel gains between all SRs and the ith ST. To simplify notations, we group all $\tilde{\mathbf{F}}_i$ into a single $NL \times NL$ matrix $\tilde{\mathbf{F}} = [\tilde{\mathbf{F}}_1 \ldots \tilde{\mathbf{F}}_N]$.

2.4.2 IA Precoding and Filtering

Let us assume an $L \times 1$ non-zero reference vector $\mathbf{v}$ along which the interference should be aligned. It should be noted that the STs are assumed to know the alignment direction $\mathbf{v}$ and to have perfect CSI knowledge about the channel coefficients $\mathbf{F}_i$ towards the PR. In this context, the following precoding scheme can be employed to align the interference

$$\mathbf{x}_i = \mathbf{w}_i x_i = (\mathbf{F}_i)^{-1} \mathbf{v} v_i x_i, \tag{2.9}$$

where $\|\mathbf{v}\|^2 = L$ and $\mathbb{E}[\mathbf{x}_i^{\dagger}\mathbf{x}_i] \leq L\gamma$. The scaling variable v_i is needed to ensure that the input power constraint is not violated for each ST. This precoding results in unit multiplexing gain and is by no means the optimal IA scheme, but it serves as a tractable way of evaluating the IA performance. Following this approach, the cochannel interference can be expressed as:

$$\sum_{i=1}^{N} \mathbf{F}_i \mathbf{x}_i = \sum_{i=1}^{N} \mathbf{F}_i \,(\mathbf{F}_i)^{-1} \mathbf{v} v_i x_i = \mathbf{v} \sum_{i=1}^{N} v_i x_i. \tag{2.10}$$

It can be easily seen that interference has been aligned across the reference vector and it can be removed using an $M \times L$ zero-forcing filter $\mathbf{Q}$ designed in such a way that $\mathbf{Q}$ is a truncated unitary matrix [7] and $\mathbf{Q}\mathbf{v} = \mathbf{0}$. After filtering, the $M \times 1$ received signal vector at the PR can be expressed as:

$$\bar{\mathbf{y}}_1 = \bar{\mathbf{H}}\mathbf{x} + \bar{\mathbf{z}}_1, \tag{2.11}$$

where $\bar{\mathbf{H}} = \mathbf{Q}\mathbf{H}$ is the $M \times M$ filtered channel matrix. The received signal at the joint processor of the SRs can be written as:

$$\bar{\mathbf{y}}_2 = \sum_{i=1}^{N} \bar{\mathbf{F}}_i x_i + \tilde{\mathbf{H}}\mathbf{x} + \mathbf{z}_2, \tag{2.12}$$

where $\bar{\mathbf{F}}_i = \tilde{\mathbf{F}}_i \,(\mathbf{F}_i)^{-1} \mathbf{v} v_i$ are the equivalent $NL \times 1$ channel matrices including precoding. To simplify notations, we group all $\bar{\mathbf{F}}_i$ into a single $NL \times N$ matrix $\bar{\mathbf{F}} = [\bar{\mathbf{F}}_1 \ldots \bar{\mathbf{F}}_N]$. In the following paragraphs, we describe three different IA approaches. The detailed mathematical formulations of these techniques and the theoretical proof that the coordinated approach can perfectly protect the primary rate can be found in [57].

2.4.2.1 Static Approach

In this approach, $\mathbf{v}$ is predefined and does not depend on the channel state. It can be noted that this is quite static but also a simple solution which assumes no coordination in the network. The disadvantage is that a large amount of received power may be filtered out since the IA direction may be aligned with one of the strong eigenvectors of the random PR-PT channel.

2.4.2.2 Uncoordinated Approach

This approach assumes that the primary and the secondary systems do not coordinate. Furthermore, the STs are aware of their CSI towards the PR but have no information about the CSI of the PT. In this context, the STs select $\mathbf{v}$ in order to maximize the secondary throughput. Subsequently, the PR senses the $\mathbf{v}$ and applies the appropriate filter $\mathbf{Q}$.

2.4.2.3 Coordinated Approach

In this approach, the primary and secondary systems coordinate to exchange the CSI and the alignment vector. The selection of $\mathbf{v}$ takes place at the PR and is subsequently communicated to the STs. It is assumed that the channel coherence time is adequate for the alignment direction to be fed back and used by the STs. This is an egoistic approach since the PR dictates the behavior of the STs in order to maximize the performance of the primary system. The coordinated approach perfectly protects the primary rate as reflected in numerical results in Sect. 2.5.

In order to evaluate the system performance of the above techniques, the following two different metrics are considered. The sum-rate capacity of the considered coexistence system is dictated by the primary throughput and the secondary average per-link throughput, let us denote by $\mathrm{C}_{\mathrm{sys}}$ and define as

$$\mathrm{C}_{\mathrm{sys}} = \mathrm{C}_{\mathrm{ps}} + \frac{\mathrm{C}_{ss}}{N}, \tag{2.13}$$

where C_{ps} is the throughput of the primary system in the presence of the secondary system, C_{ss} is the average per-link rate of the secondary system in the presence of the primary system, and N is the number of SUs. It should be noted that in (2.13), we consider secondary average per-link throughput i.e., $\frac{\mathrm{C}_{ss}}{N}$ in order to reflect the secondary per-user throughput as we increase the number of SUs in the system, as illustrated with the help of numerical results in Sects. 5.1 and 5.2. Subsequently, the primary rate protection ratio is denoted by PR and defined as:

$$\mathrm{PR} = \frac{\mathrm{C}_{\mathrm{ps}}}{\mathrm{C}_{\mathrm{po}}}, \tag{2.14}$$

where C_{po} denotes the primary only capacity in the absence of the secondary system.

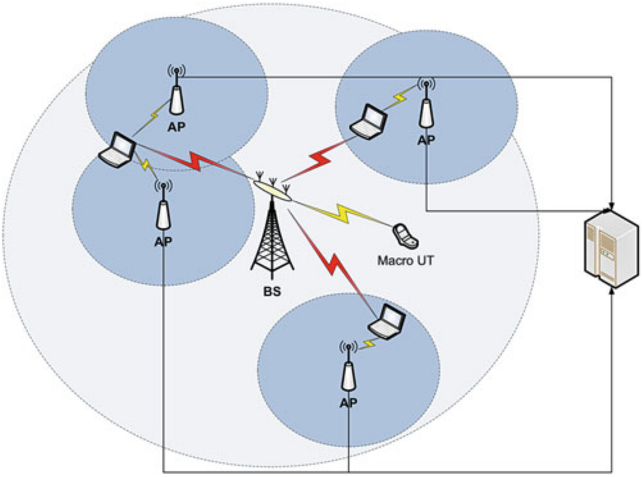


Fig. 2.2 Spectral coexistence scenario of femtocells (secondary) and a macrocell (primary) system using IA

2.5 Practical Scenarios

In this section, we mention two important applications of the IA technique in terrestrial and satellite paradigms based on the generic system and signal models presented in Sect. 2.4. Although these two systems have different characteristics and channel models, they can be studied using the same input-output equations. Furthermore, both systems operate in a normal uplink mode with the primary system as a single user uplink and the secondary system as a multiuser uplink. The only difference between the considered satellite and terrestrial models is that in the terrestrial scenario, IA is over the spatial dimensions and in the satellite scenario, IA is over the subcarriers.

2.5.1 Macrocell-Femtocell Coexistence in Spatial Domain

Let us consider a coexistence scenario of a macrocell and a femtocell systems, both operating in normal uplink mode as shown in Fig. 2.2. The femtocell UTs are STs, femtocell access points (APs) are the SRs, a macro UT is the PT and a macro BS is the PR. Let us consider a coverage area where a single macrocell operates receiving signals from a set of PUs. A number of femtocells (N) operate over the same coverage area receiving signals from a set of SUs. Furthermore, the femtocells are able of cooperating through a broadband backhaul and jointly decoding the received signals. After scheduling, we consider that for a single slot one macro UT and N femtocell UTs are transmitting simultaneously over a common set of frequencies.

Since the macrocell system is the primary, interference coming from the femtocell UTs has to be suppressed. On the other hand, the interference of the macro UT towards the femtocell APs has to be tolerated as the small cell system is secondary. We consider that the macro UT has M antennas while the BS, small cell UTs and the AP have $L = M + 1$ antennas. Furthermore, it is assumed that the interference caused by the small cell UTs have CSI towards the macro BS and this can be easily measured by listening to the macrocell pilot signals.

The considered channel model is based on a MIMO Rayleigh channel whose power is scaled according to a power-law path loss model i.e., asymmetric power levels. More specifically,

$$\mathbf{H} = \alpha \mathbf{G}, \tag{2.15}$$

where α is the path loss coefficient between the BS and the macro UT and $\mathbf{G}$ is an $L \times M$ random matrix with complex circularly symmetric (c.c.s.) i.i.d. elements representing Rayleigh fading coefficients.

The performance of three different IA approaches mentioned in Sect. 2.4 have been compared with the resource division and no-mitigation techniques in [11, 57]. Based on the simulation parameters and environment considered in [57], Fig. 2.3 presents the normalized system rate ($\mathrm{C}_{\mathrm{sys}}$) versus number of femtocells (N) for the terrestrial coexistence scenario of femtocells and a macrocell. While simulating this scenario, a macro UT and femtocell UTs are considered to be uniformly distributed within the coverage area of the BS and the APs respectively. From the figure (Fig. 2.3), it can be depicted that the sum-rate slowly increases with the value of N for all the considered techniques. The no-mitigation scheme achieves a three-fold gain while other techniques achieve a two-fold gain compared to primary only transmission, however this technique does not protect the primary rate as reflected in Fig. 2.4. Figure 2.4 shows the primary rate protection ratio versus N plots for different techniques. It can be noted that the coordinated IA technique fully protects the primary rate as expected, while other IA techniques preserve roughly 70 % and the resource division preserves 82 % of the primary rate. Furthermore, all techniques except no-mitigation preserve a constant protection rate with increasing N, while the performance of no-mitigation technique degrades monotonically.

2.5.2 *Multibeam-Monobeam Satellite Coexistence in Frequency Domain*

Recent contributions exploiting spectrum sharing opportunities in satellite communications include [32, 54–59, 61, 67, 69, 76]. The existing cognitive SatComs literature can be categorized into the following: (i) hybrid satellite-terrestrial coexistence scenario [32,54,56,58,59,76] and (ii) dual satellite coexistence scenario [55, 57, 60, 67]. In this section, we present a dual coexistence scenario consisting of

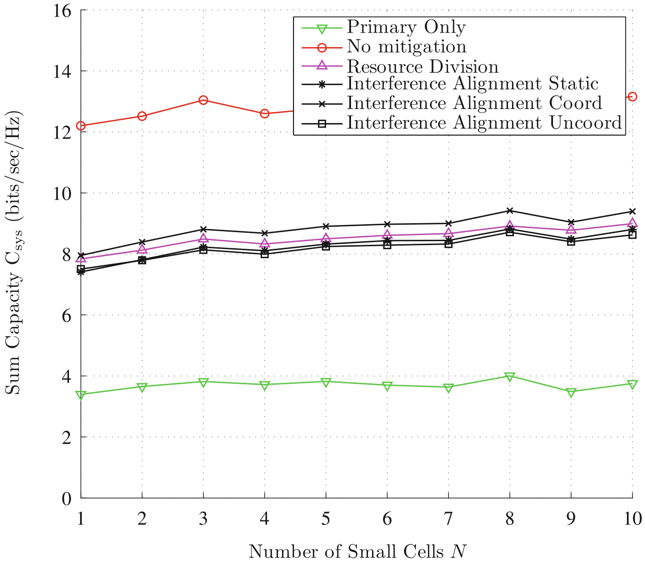


Fig. 2.3 Performance comparison of different techniques in terms of the normalized system rate versus number of small cells N in the considered terrestrial coexistence paradigm

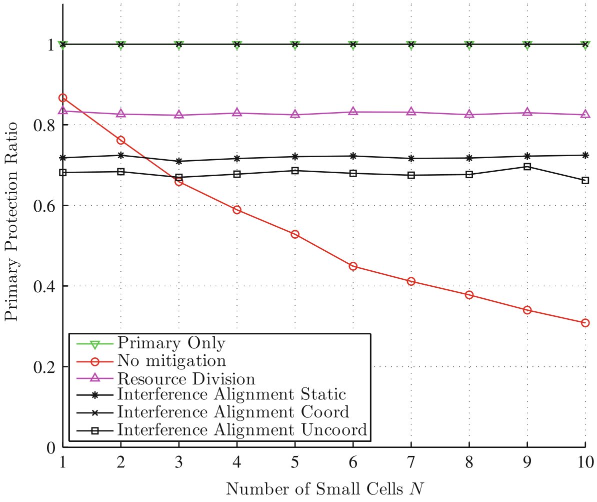


Fig. 2.4 Performance comparison of different techniques in terms of the primary protection ratio versus number of small cells N in the considered terrestrial coexistence paradigm

two multibeam satellites using the IA technique in order to mitigate the interference of multibeam satellite terminals towards the monobeam satellite.

Let us consider one monobeam satellite (SAT1) and one multibeam satellite (SAT2) covering the same area as shown in Fig. 2.5. It can be assumed that they

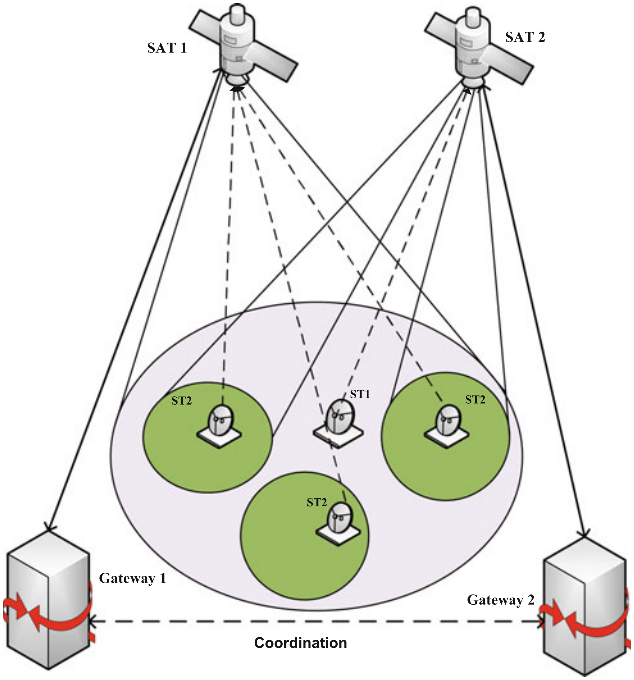


Fig. 2.5 Spectral coexistence scenario of a monobeam satellite (primary) and a multibeam satellite (secondary)

communicate with different gateways on the surface of the Earth. The monobeam satellite uses a single beam to provide coverage to the given area, whereas the multibeam satellite uses several beams to provide coverage to the same area. From the perspective of spectral coexistence, we consider the monobeam system as the primary and the multibeam system as the secondary i.e., the monobeam satellite SAT1 is the PR, the feeders of multibeam satellite SAT2 are the SRs, the multibeam satellite terminals ST2s are the STs and the monobeam satellite terminal ST1 is the PT. In this aspect, the multibeam satellite has to tolerate the interference coming from the monobeam satellite terminal. However, the interference coming from multibeam satellite terminals towards the monobeam satellite has to be suppressed. In this aspect, the IA technique can be applied at the multibeam satellite terminals to mitigate the interference towards the primary satellite.

We consider a single ST1, N number of ST2s served by N beams of SAT2. Multibeam joint processing is considered at the gateway of SAT2 to decode the received signals from ST2s jointly. Since a single gateway is responsible for processing the transmitted and received signals corresponding to a large geographic area, the application of joint processing techniques in the satellite context is centralized. After scheduling, we consider that one ST1 and N number of ST2s are transmitting simultaneously in a single slot over a common spectrum band. In this context, we consider spatial multiplexing for the primary monobeam system and we employ multiple dimensions (carriers) in the secondary multibeam system to align interference with the reference vector. Furthermore, we consider that all the satellite terminals use multicarrier transmission scheme and the IA is employed at the ST2s over $L = M + 1$ carriers, affected by Adjacent Carrier Interference (ACI). We consider that M number of symbols are transmitted by the ST1 and 1 symbol per ST2 is transmitted by spreading across all the carriers. Furthermore, it should be noted that ST1 sends M symbols over M subcarriers whereas each ST2 sends 1 symbol over L subcarriers. To suppress the interference caused by ST2s using the IA technique, CSI towards the SAT1 is required and we assume that this CSI can be acquired at the ST2s by listening to the pilot signals broadcasted from the gateway.

Each transmit/receive node consists of a single antenna and uses multicarrier transmission so that the channels can be represented as diagonal matrices, where the diagonal entries correspond to different sub-channels. The multicarrier model considered in this scenario differs from MIMO (spatial) channel matrix with full entries as considered in the terrestrial scenario. Due to imperfect bandpass filters, weak copies of adjacent carrier signals may leak into the central carrier causing ACI. Therefore, we consider a multicarrier channel model with ACI. We assume that each carrier goes through independent flat-fading channels. The multi-carrier channel matrix with ACI for the ith satellite link for L number of carriers can be written as

$$\mathbf{H} = \begin{bmatrix} h_1 & \sqrt{\rho}h_2 & \dots & 0 \\ \sqrt{\rho}h_1 & h_2 & \dots & 0 \\ 0 & \sqrt{\rho}h_2 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & h_{L-1} & \sqrt{\rho}h_L \\ 0 & 0 & \sqrt{\rho}h_{L-1} & h_L \end{bmatrix}, \tag{2.16}$$

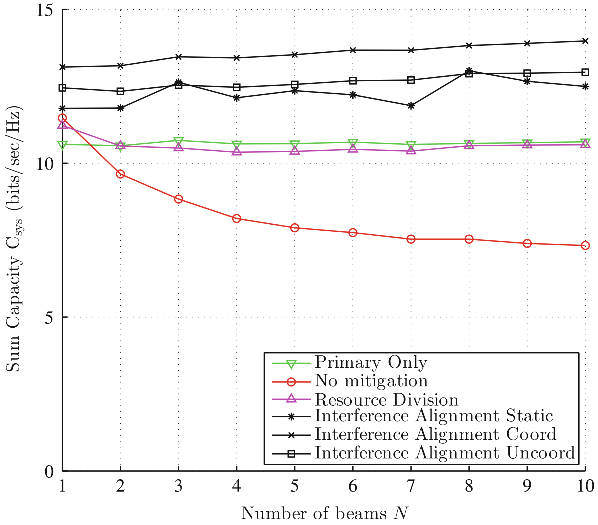
where ρ represents the fraction of carrier power leaked to adjacent carriers and the parameter h_i represents the Rician fading coefficient, given by;

$$h_i = \left(\sqrt{\frac{R}{R+1}} l + \sqrt{\frac{1}{R+1}} g_i \right), \tag{2.17}$$

where R is the Rician factor, l is a deterministic parameter representing the Line of Sight (LoS) component and g_i is a c.c.s. i.i.d. element for the i-th satellite link representing the Rayleigh fading coefficient.

In the considered satellite coexistence scenario with the simulation parameters in [57], Fig. 2.6 depicts the normalized system rate ($\mathrm{C_{sys}}$) versus number of SAT2 beams N for different techniques and it can be observed that the coordinated

Fig. 2.6 Performance comparison of different techniques in terms of the normalized system rate versus number of SAT2 beams N in the considered satellite coexistence paradigm



IA technique performs better than all other techniques and the sum-rate slowly increases with N for this technique. The sum-rate for uncoordinated IA technique is worse than the coordinated IA technique and is still better than other considered techniques and it increases slowly with the value of N. Furthermore, the sum-rate for no mitigation technique decreases with the value of N, remains more or less constant with the value of N for resource division and remains constant for the primary only transmission. Since this scenario uses different channel i.e., Rician fading channel, the sum rate results in Fig. 2.6 differ from that of the results Fig. 2.3. It should be noted that in the considered satellite coexistence scenario, we use a non-zero mean channel and consider a tridiagonal channel matrix with three correlated entries.

Figure 2.7 depicts the PR versus N plot for different techniques. It can be observed that the coordinated IA technique is optimal and matches with the primary only technique. This means that the coordinated IA technique fully protects the primary rate. Furthermore, all techniques except the no-mitigation technique shows a constant protection rate with the value of N, while the performance of no-mitigation decreases monotonically as in previous scenario. Moreover, the uncoordinated IA technique protects almost 90 % of the total primary rate and the resource division protects about 65 % of the total primary rate. To enhance the spectrum efficiency further, authors in [13] investigate the effect of the frequency packing in IA based dual satellite cognitive systems and show that the sum-rate increases with the value of frequency packing factor for all the considered IA techniques with the IA coordinated technique perfectly protecting the primary rate for all the considered frequency packing factor (from 0.5 to 1).

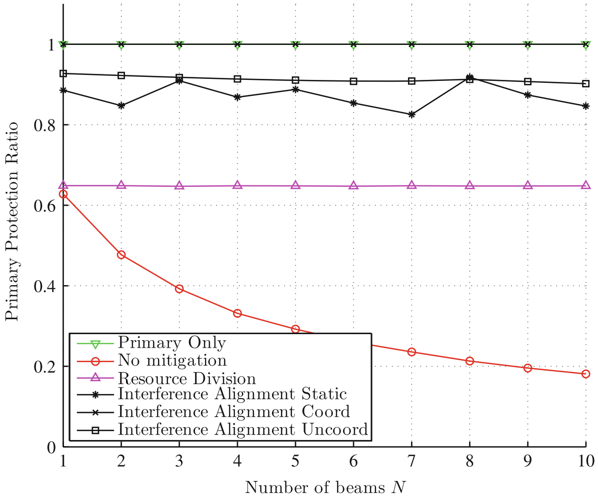


Fig. 2.7 Performance comparison of different techniques in terms of the primary protection ratio versus number of SAT2 beams N in the considered satellite coexistence paradigm

2.6 Practical Challenges of IA

The main practical limitations of IA techniques are requirement of large dimensionality of interference networks, very high SNR, CSI knowledge and strict synchronization [17]. Other challenges include the overhead for acquiring enough channel knowledge, the penalty of residual channel uncertainty at the transmitters, impact of channel correlations, tracking the IA solution under time varying channels. The main challenge of IA from practical perspectives are listed below.

- In many cases except in the distributed IA, the global channel knowledge is required to carry out the IA operation and in distributed IA techniques, local CSI knowledge is needed. It's a crucial aspect to investigate suitable blind and semiblind IA techniques so that the burden for acquiring the channel knowledge is reduced.
- The number of alignment constraints grows very rapidly as the number of interfering users is increased. For example, in a K user interference channel, each of the K receivers needs an alignment of $K-1$ interfering signal spaces for a total of $O(K^2)$ signal space alignment constraints. Since there are only K signal subspaces are available to satisfy $O(K^2)$ signal space alignment constraints, the problem can become infeasible [27].
- Limited diversity of interference channels may also limit the relativity of the alignment. For example, when each node has only one antenna and all channels are constant across time and frequency, the diversity of channels becomes limited.
- The practical achievable scheme which requires finite dimensions for the case of multiple non-intended receivers is still an open research problem. In this context, exploring innovative methods for the optimization of linear precoders

and alignment filters in order to maximize the sum-rate in low and moderate SNR regions is an important future research issue.

2.7 Chapter Summary

Cognitive IA technique could be an effective technique in order allow the coexistence of different wireless networks. In this context, this chapter provides an overview of existing IA techniques along with the principle of IA and the concept of the DoF metric. Furthermore, various existing IA approaches in the context of CR networks have been briefly discussed. Moreover, a general framework for spectral coexistence of wireless networks have been presented and interference alignment and filtering processes have been explained. In addition, two practical coexistence scenarios in satellite and terrestrial paradigms have been illustrated with the help of theoretical and numerical analysis. In addition, several practical challenges of this technique have been identified in order to enable the future research in this domain.

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References

1. Abdelhamid, B., ElSabrouty, M., Elramly, S.: Novel interference alignment in multi-secondary users cognitive radio system. In: 2012 IEEE Symposium on Computers and Communications (ISCC), Cappadocia, pp. 000,785–000,789 (2012)
2. Amir, M., El-Keyi, A., Nafie, M.: Constrained interference alignment and the spatial degrees of freedom of MIMO cognitive networks. IEEE Trans. Inf. Theory **57**(5), 2994–3004 (2011)
3. Badic, B., O’Farrrell, T., Loskot, P., He, J.: Energy efficient radio access architectures for green radio: large versus small cell size deployment. In: IEEE 70th Vehicular Technology Conference, Anchorage, pp. 1–5 (2009)
4. Bresler, G., Parekh, A., Tse, D.: The approximate capacity of the many-to-one and one-to-many Gaussian interference channels. IEEE Trans. Inf. Theory **56**(9), 4566–4592 (2010)
5. Cadambe, V., Jafar, S.: Interference alignment and degrees of freedom of the K-user interference channel. IEEE Trans. Inf. Theory **54**(8), 3425–3441 (2008)
6. Cadambe, V., Jafar, S.: Interference alignment and spatial degrees of freedom for the K user interference channel. In: IEEE International Conference on Communications, Beijing, pp. 971–975 (2008)
7. Cadambe, V., Jafar, S.: Interference alignment and the degrees of freedom of wireless X networks. IEEE Trans. Inf. Theory **55**(9), 3893–3908 (2009)
8. Cadambe, V., Jafar, S., Wang, C.: Interference alignment with asymmetric complex signaling–settling the Høst-Madsen-Nosratinia conjecture. IEEE Trans. Inf. Theory **56**(9), 4552–4565 (2010)

9. Chatzinotas, S., Ottersten, B.: Interference alignment for clustered multicell joint decoding. In: IEEE Wireless Communications and Networking Conference, Cancun, pp. 1966–1971 (2011)
10. Chatzinotas, S., Ottersten, B.: Interference mitigation techniques for clustered multicell joint decoding systems. EURASIP J. Wirel. Commun. Netw. Spec. Issue Multicell Coop. Next Gener. Commun. Syst. **2011**(1), 132 (2011)
11. Chatzinotas, S., Ottersten, B.: Cognitive interference alignment between small cells and a macrocell. In: 19th International Conference on Telecommunications, Jounieh, pp. 1–6 (2012)
12. Chatzinotas, S., Zheng, G., Ottersten, B.: Joint precoding with flexible power constraints in multibeam satellite systems. In: IEEE Global Telecommunications Conference, Houston, pp. 1–5 (2011)
13. Chatzinotas, S., Sharma, S.K., Ottersten, B.: Frequency packing for interference alignment-based cognitive dual satellite systems. In: IEEE Vehicular Technology Conference Fall, Las Vegas (2013)
14. Chen, G., Xiang, Z., Xu, C., Tao, M.: On degrees of freedom of cognitive networks with user cooperation. IEEE Wirel. Commun. Lett. **1**(6), 617–620 (2012)
15. Da, B., Zhang, R.: Exploiting interference alignment in multi-cell cooperative OFDMA resource allocation. In: IEEE Global Telecommunications Conference, Houston, pp. 1–5 (2011)
16. Du, H., Ratnarajah, T.: Robust joint signal and interference alignment for MIMO cognitive radio network. In: 2012 IEEE Wireless Communications and Networking Conference (WCNC), Paris, pp. 448–452 (2012)
17. El Ayach, O., Peters, S., Heath R.W., J.: The practical challenges of interference alignment. IEEE Newblock Wirel. Commun. **20**(1), 35–42 (2013)
18. Etkin, R., Tse, D., Wang, H.: Gaussian interference channel capacity to within one bit. IEEE Trans. Inf. Theory **54**(12), 5534–5562 (2008)
19. Ganesan, R., Klein, A.: Projection based space-frequency interference alignment in a multi-carrier multi-user two-way relay network. In: 8th International Symposium on Wireless Communication Systems, Aachen, pp. 266 –270 (2011)
20. Goldsmith, A., Jafar, S., Maric, I., Srinivasa, S.: Breaking spectrum gridlock with cognitive radios: an information theoretic perspective. Proc. IEEE **97**(5), 894–914 (2009)
21. Gomadam, K., Cadambe, V., Jafar, S.: Approaching the capacity of wireless networks through distributed interference alignment. In: IEEE Global Telecommunications Conference, New Orleans, pp. 1 –6 (2008)
22. Gomadam, K., Cadambe, V., Jafar, S.: A distributed numerical approach to interference alignment and applications to wireless interference networks. IEEE Trans. Inf. Theory **57**(6), 3309–3322 (2011)
23. Gou, T., Wang, C., Jafar, S.: Aiming perfectly in the dark-blind interference alignment through staggered antenna switching. IEEE Trans. Signal Process. **59**(6), 2734–2744 (2011)
24. Guler, B., Yener, A.: Interference alignment for cooperative MIMO femtocell networks. In: 2011 IEEE Global Telecommunications Conference (GLOBECOM 2011), Houston, pp. 1–5 (2011)
25. Huang, L., Zhu, G., Du, X.: Cognitive femtocell networks: an opportunistic spectrum access for future indoor wireless coverage. IEEE Wirel. Commun. **20**(2), 44–51 (2013)
26. Jafar, S.: Exploiting channel correlations – simple interference alignment schemes with no CSIT. In: 2010 IEEE Global Telecommunications Conference (GLOBECOM 2010), Miami, pp. 1–5 (2010)
27. Jafar, S.A.: Interference alignment – a new look at signal dimentions in a communication network. Found. Trends Commun. Inf. Theory **7**(1), 1–134 (2010)
28. Jafar, S., Shamai, S.: Degrees of freedom region of the MIMO X channel. IEEE Trans. Inf. Theory **54**(1), 151–170 (2008)
29. Jafar, S., Cadambe, V., Wang, C.: Interference alignment with asymmetric complex signaling. In: 47th Annual Allerton Conference on Communication, Control, and Computing (Allerton 2009), Piscataway, pp. 991–996 (2009)

30. Jain, P., Vazquez-Castro, M.: Subspace interference alignment for multibeam satellite communications systems. In: 5th Advanced Satellite Multimedia Systems Conference and the 11th Signal Processing for Space Communications Workshop, Sardinia, pp. 234–239 (2010)
31. Jung, B.C., Park, D., Shin, W.Y.: Opportunistic interference mitigation achieves optimal degrees-of-freedom in wireless multi-cell uplink networks. IEEE Trans. Commun. **60**(7), 1935–1944 (2012)
32. Kandeepan, S., De Nardis, L., Di Benedetto, M.G., Guidotti A., Corazza G.: Cognitive satellite terrestrial radios. In: IEEE GLOBECOM, Miami, pp. 1–6 (2010)
33. Kang, M., Choi, W.: Ergodic interference alignment with delayed feedback. IEEE Signal Process. Lett. **20**(5), 511–514 (2013)
34. Koo, B., Park, D.: Interference alignment with cooperative primary receiver in cognitive networks. IEEE Commun. Lett. **16**(7), 1072–1075 (2012)
35. Lejosne, Y., Slock, D., Yuan-Wu, Y.: Degrees of freedom in the MISO BC with delayed-CSIT and finite coherence time: optimization of the number of users. In: 2012 6th International Conference on Network Games, Control and Optimization (NetGCooP), Paris, pp. 80–85 (2012)
36. Lertwiram, N., Popovski, P., Sakaguchi, K.: A study of trade-off between opportunistic resource allocation and interference alignment in femtocell scenarios. IEEE Wirel. Commun. Lett. **1**(4), 356–359 (2012)
37. Li, H.: Linear interference alignment based on signal and interference space ranks. In: 4th IET International Conference on Wireless, Mobile Multimedia Networks (ICWMMN 2011), Beijing, pp. 169–172 (2011)
38. Liu, T., Yang, C.: Signal alignment for multicarrier code division multiple user two-way relay systems. IEEE Trans. Wirel. Commun. **10**(11), 3700–3710 (2011)
39. Maleki, H., Jafar, S., Shamai, S.: Retrospective interference alignment over interference networks. IEEE J. Sel. Top. Signal Process. **6**(3), 228–240 (2012)
40. Maso, M., Cardoso, L.S., Debbah, M.: Orthogonal LTE Two-Tier Cellular Networks, Communication (ICC), 2011. IEEE International Conference on, **1**(5), 5–9 (2011)
41. Masucci, A., Tulino, A., Debbah, M.: Asymptotic analysis of uplink interference alignment in ricean small cells. In: IEEE Global Telecommunications Conference, Houston (2011)
42. Nazer, B., Gastpar, M., Jafar, S., Vishwanath, S.: Ergodic interference alignment. IEEE Trans. Inf. Theory **58**(10), 6355–6371 (2012)
43. Nguyen, T.M., Quek, T., Shin, H.: Opportunistic interference alignment in MIMO femtocell networks. In: 2012 IEEE International Symposium on Information Theory Proceedings (ISIT), Cambridge, pp. 2631–2635 (2012)
44. Ordentlich, O., Erez, U.: On the robustness of lattice interference alignment. IEEE Trans. Inf. Theory **59**(5), 2735–2759 (2013)
45. Pantisano, F., Bennis, M., Saad, W., Debbah, M., Latva-aho, M.: Interference alignment for cooperative femtocell networks: a game-theoretic approach. IEEE Trans. Mobile Comput. **12**(11), 2233–2246 (2012)
46. Parker, P.A., Bliss, D., Tarokh, V.: On the degrees-of-freedom of the MIMO interference channel. In: 42nd Annual Conference on Information Sciences and Systems (CISS 2008), Princeton, pp. 62–67 (2008)
47. Perlaza, S., Debbah, M., Lasaulce, S., Chaufray, J.M.: Opportunistic interference alignment in MIMO interference channels. In: IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2008), Cannes, pp. 1–5 (2008)
48. Perlaza, S., Fawaz, N., Lasaulce, S., Debbah, M.: From spectrum pooling to space pooling: opportunistic interference alignment in MIMO cognitive networks. IEEE Trans. Signal Process. **58**(7), 3728–3741 (2010)
49. Peters, S., Heath, R.: Interference alignment via alternating minimization. In: IEEE International Conference on Acoustics, Speech and Signal Processing, Taipei, pp. 2445–2448 (2009)
50. Razavi, S., Ratnarajah, T., Masouros, C., Sellathurai, M.: Joint interference and phase alignment in multiuser MIMO interference channels. In: 2012 Conference Record of the Forty Sixth Asilomar Conference on Signals, Systems and Computers (ASILOMAR), Pacific Grove, pp. 1137–1141 (2012)

51. Razaviyayn, M., Sanjabi, M., Luo, Z.Q.: Linear transceiver design for interference alignment: complexity and computation. IEEE Trans. Inf. Theory **58**(5), 2896–2910 (2012)
52. Schmidt, D., Shi, C., Berry, R., Honig, M., Utschick, W.: Minimum mean squared error interference alignment. In: 2009 Conference Record of the Forty-Third Asilomar Conference on Signals, Systems and Computers, Pacific Grove, pp. 1106–1110 (2009)
53. Schreck, J., Wunder, G.: Distributed interference alignment in cellular systems: Analysis and algorithms. In: 11th European Wireless Conference 2011 – Sustainable Wireless Technologies (European Wireless), Vienna, Austria, pp. 1–8 (2011)
54. Sharma, S.K., Chatzinotas, S., Ottersten, B.: Satellite cognitive communications: interference modeling and techniques selection. In: 6th ASMS/SPSC Conference, Baiona, pp. 111–118 (2012)
55. Sharma, S.K., Chatzinotas, S., Ottersten, B.: Exploiting polarization for spectrum sensing in cognitive SatComs. In: 7th International Conference CROWNCOM, Stockholm, pp. 36–41 (2012)
56. Sharma, S.K., Chatzinotas, S., Ottersten, B.: Spectrum sensing in dual polarized fading channels for cognit SatComs. In: IEEE Globecom Conference, Anaheim, pp. 3443–3448 (2012)
57. Sharma, S.K., Chatzinotas, S., Ottersten, B.: Interference alignment for spectral coexistence of heterogeneous networks. EURASIP J. Wirel. Commun. Netw. **46** (2013). doi:10.1186/1687-1499-2013-46
58. Sharma, S.K., Chatzinotas, S., Ottersten, B.: Transmit beamforming for spectral coexistence of satellite and terrestrial networks. In: 8th International Conference CROWNCOM, Washington, D.C., pp. 275–281 (2013)
59. Sharma, S.K., Chatzinotas, S., Ottersten, B.: Spatial filtering for underlay cognitive SatComs. In: Proceedings of the 5th International Conference PSATS, Toulouse (2013)
60. Sharma, S.K., Chatzinotas, S., Ottersten, B.: Cognitive beamhopping for spectral coexistence of multibeam satellites. In: Future Network Mobile Summit, Lisbon (2013)
61. Sharma, S.K., Chatzinotas, S., Ottersten, B.: Cognitive radio techniques for satellite communication systems. In: IEEE VTC-fall, Las Vegas (2013)
62. Shi, C., Berry, R., Honig, M.: Interference alignment in multi-carrier interference networks. In: IEEE International Symposium on Information Theory Proceedings, Saint Petersburg, pp. 26–30 (2011)
63. Shin, W., Lee, N., Lim, J.B., Shin, C., Jang, K.: On the design of interference alignment scheme for two-cell MIMO interfering broadcast channels. IEEE Trans. Wirel. Commun. **10**(2), 437–442 (2011)
64. Suh, C., Tse, D.: Interference alignment for cellular networks. In: 46th Annual Allerton Conference on Communication, Control, and Computing, Urbana-Champaign, IL, pp. 1037–1044 (2008)
65. Telatar, E.: Capacity of multi-antenna Gaussian channels. Eur. Trans. Telecommun. ETT **10**(6), 585–596 (1999)
66. Tresch, R., Guillaud, M., Riegler, E.: On the achievability of interference alignment in the K-user constant MIMO interference channel. In: IEEE/SP 15th Workshop on Statistical Signal Processing, Cardiff, pp. 277–280 (2009)
67. Vassaki, S., Poulakis, M.I., Panagopoulos, A.D., Constantinou, P.: Power allocation in cognitive satellite terrestrial networks with QoS constraints. IEEE Commun. Lett. **17**(7), 1344–1347 (2013)
68. Vaze, C., Varanasi, M.: The degree-of-freedom regions of MIMO broadcast, interference, and cognitive radio channels with no CSIT. IEEE Trans. Inf. Theory **58**(8), 5354–5374 (2012)
69. Wang. L.N., Wang, B.: Distributed power control for cognitive satellite networks. Adv. Mater. Res. Mechatron. Intell. Mater. II **71**, 1156–1160 (2012)
70. Wang, C., Gou, T., Jafar, S.: Subspace alignment chains and the degrees of freedom of the three-user MIMO interference channel. In: 2012 IEEE International Symposium on Information Theory Proceedings (ISIT), Cambridge, pp. 2471–2475 (2012)

71. Weingarten, H., Steinberg, Y., Shamai, S.: The capacity region of the Gaussian multiple-input multiple-output broadcast channel. IEEE Trans. Inf. Theory **52**(9), 3936–3964 (2006)
72. Weingarten, H., Shamai, S., Kramer, G.: On the compound MIMO broadcast channel. In: Proceedings of Annual Information Theory and Applications Workshop UCSD, San Diego (2007)
73. Yang, L., Zhang, W.: On design of asymmetric interference alignment and cancelation scheme in MIMO X network. In: 2011 International Conference on Wireless Communications and Signal Processing (WCSP), Nanjing, pp. 1–5 (2011)
74. Yang, L., Zhang, W.: Asymmetric interference alignment and cancelation for 3-user MIMO interference channels. In: 2012 IEEE International Conference on Communications (ICC), Sydney, pp. 2260–2264 (2012)
75. Yetis, C., Gou, T., Jafar, S., Kayran, A.: On feasibility of interference alignment in MIMO interference networks. IEEE Trans. Signal Process. **58**(9), 4771–4782 (2010)
76. Yun, Y.H., Cho, J.H.: An orthogonal cognitive radio for a satellite communication link. In: IEEE 20th International Symposium PIMRC, Tokyo, pp. 3154–3158 (2009)