COGNITIVE RADIO NETWORKS

Interference Cancelation and Management Techniques

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Radio spectrum is a scarce and precious natural resource that is significantly underutilized with current fixed spectrum-licensing policies [1]. This has inspired the development of hierarchical spectrum-sharing systems, where secondary systems are allowed to access the underutilized spectrum of incumbents without causing harmful interference to legacy/primary systems. In this article, we are interested in an important paradigm of secondary systems known as cognitive radio (CR) networks [2], [3], where the secondary terminals are envisioned to be capable of sensing and reasoning about the operating radio environments and thereby autonomously adjusting their transceiver parameters to exploit the underutilized radio resources in a dynamic fashion.

Because of its spectrum-sharing nature, a CR network inevitably operates in interference-intensive environments. Effective interference management is therefore essential to the coexistence of primary and CR networks. Interference management mechanisms can be embedded into a CR network in various aspects of system design from network planning, radio resource management, medium access control (MAC) to physical-layer signal processing. Our interest in this study lies on the physical-layer signal-processing schemes, commonly known as interference cancelation (IC) techniques. In the literature, only a few articles [4]–[7] have studied IC techniques in the context of CR networks. In [4], an opportunistic IC scheme was proposed for CR receivers to adaptively cancel the primary signals when they are decodable. In [5]–[7], active spectrum shaping, transmit beamforming, and transmit precoding techniques were investigated for CR transmitters, respectively. Apart from the aforementioned articles, there exist many other IC techniques [8] that have been proposed and successfully applied to a number of wireless systems to mitigate various types of interference. The widely used IC techniques include the filter-based approach (e.g., Wiener filter), transform-domain approach (e.g., wavelet, chirplet), cyclostationarity-based approach, higher order statistics-based approach, joint detection/multiuser detection (MUD), and spatial processing (e.g., beamforming). The success of these IC techniques inspires us to study their applications to CR networks.

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The rest of this article is organized as follows. We first present the methodologies of assessing interference in CR networks and the corresponding interference models. We then review a number of existing IC techniques applicable to CR receivers and transmitters and discuss their pros and cons. Finally, hybrid IC techniques are introduced and conclusions are drawn.

Interference Assessment and Modeling

Interference in the context of CR networks can be classified into two types: intra- and internetwork interference. Intranetwork interference, also known as self-interference, refers to the interference caused within one network (either a primary or CR network). Typical examples of intranetwork interference include intersymbol interference in frequency-selective channels and multiaccess interference (MAI) in multiuser networks. Intranetwork interference exists to some extent in every wireless communication system, and there is a wealth of techniques established to mitigate them effectively. On the other hand, internetwork interference refers to the mutual interference between the primary and CR networks. The problem of internetwork-interference management is twofold. First, CR transmitters need to carefully control their emissions to guarantee that the quality of service (QoS) of the primary network is not harmfully degraded by the interfering secondary signals. Second, CR receivers should be able to effectively combat the interference from primary networks to successfully decode secondary signals and provide useful QoS in the CR network. The problem of internetwork-interference management is extremely important for CR networks and is the focus of this article. Before we evaluate the IC techniques in CR networks, it is desirable to first study the characteristics of the interference that is targeted to be canceled.

Interference from CR to Primary Networks

As a new metric to assess the interference in spectrum-sharing systems, the interference temperature model has recently been proposed in [2]. Unlike traditional transmittercentric approaches that seek to regulate interference indirectly by controlling the emission power, time, or locations of interfering transmitters, the interference temperature model takes a receivercentric approach and aims to directly manage interference at the receiver through interference temperature limits. The interference temperature limit characterizes the worst-case interfering scenario in a particular frequency band and at a particular geographic location [2], [6]. In other words, it represents the maximum amount of interference that a receiver can tolerate.

The interference temperature model serves as a useful tool to characterize the interference from CR to primary networks. An ideal interference temperature model should account for the cumulative radio-frequency (RF) energy from multiple CR transmissions and sets a maximum cap on their aggregate level. CR users are then allowed to use a frequency band as long as their transmissions do not violate the interference temperature limits. Implementation of such an ideal interference temperature model usually requires real-time interactions between CR transmitters and primary receivers and is therefore widely regarded as impractical. To this end, several modified interference models [9], [10] have been proposed as more practical models of the interference at primary receivers.

In [9], the interference was defined as the expected fraction of primary users with services disrupted by nearby CR transmitters. Factors such as CR signal modulation, antenna gains, and power control were considered in this model. However, this model accounted only for the case where the primary services were disrupted by a single CR user, and it did not consider the aggregate effect of multiple CR transmissions. In [10], the aggregate effect was taken into account, and complex stochastic models were built to characterize the exact probability density function (PDF) of the accumulated interference power. Moreover, the interference avoidance ability of CR transmitters was considered by introducing the concept of an exclusion region. As illustrated in Figure 1, an exclusion region is defined as a disk centered at a primary receiver with a radius R. Any CR transmitter within the exclusion region is regarded as a harmful interferer and is therefore forbidden to transmit. When the locations of CR transmitters follow a Poisson point process with a density λ, the PDF of the aggregate interference can be computed as a function of R [10]. As shown in Figure 2, it is found that a slight increase of R can effectively reduce both the mean and variance of the received interference power.

Interference from Primary to CR Networks

The interference from primary to CR networks can be directly measured by CR receivers with passive sensing techniques. On the basis of power-spectrum density (PSD) of the interfering primary signals, we can broadly classify the spectra into three categories: 1) black spaces are spectra occupied by high-power primary signals, which can usually be decoded by CR receivers; 2) gray spaces refer to spectra with low to medium power primary signals, which are too weak to be decoded satisfactorily but are still significant sources of interference to the CR network; and 3) white spaces refer to spectra where primary signals have negligible power and can be simply treated as background noise.

Characterizing the distributions of white/gray/black spaces across frequency, time, and space domains are of great importance for assessing the interference faced by CR receivers. To date, such a characterization has mainly been conducted empirically by a number of measurement campaigns [1], which show that the radio spectrum consists of a high percentage of white space. A theoretical model was recently proposed in [11] to characterize the

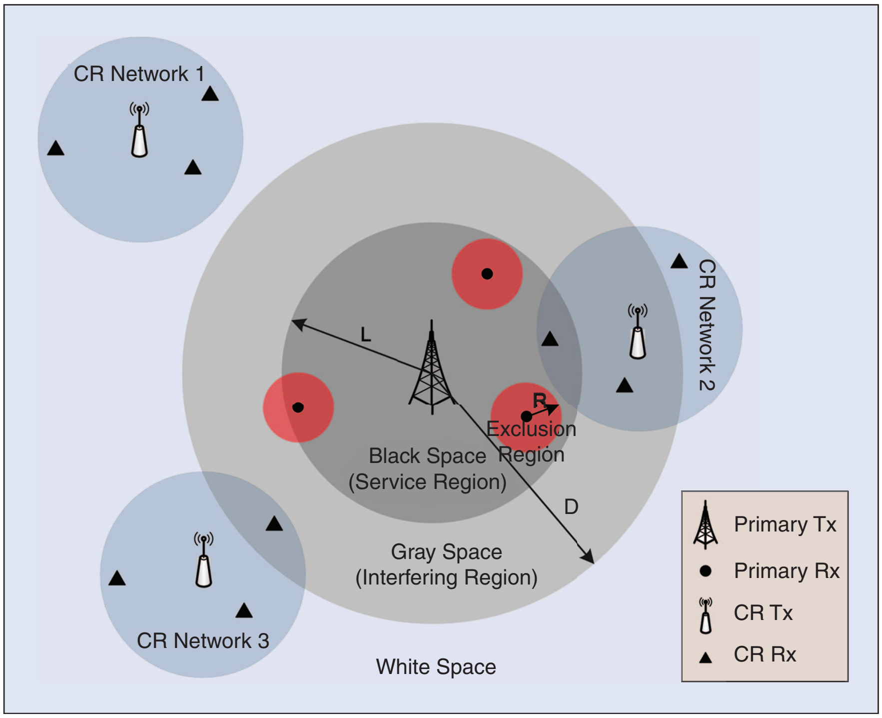

FIGURE 1 Coexistence of a primary network and randomly distributed CR networks with illustrations of the exclusion region, black space (service region), gray space (interfering region), and white space.

regarded as the interfering region. Under an intranetwork interference constraint that prohibits two active primary transmitters to lie closer than a minimum distance of $L + D$, in [11], it was found that white/gray spaces are naturally abundant but geographically fragmented. For example, when $D = 2L$, the spectra will be detected as white spaces on more than 56% of the plane and as gray spaces on more than 34% of the plane [11].

Intuitively, white spaces are the most desirable resources for CR networks to exploit, whereas gray spaces can also be reused to further improve the spectrum utilization. In contrast, there is a widespread perception that black spaces are not exploitable by CR networks because of the presence of strong interfering primary signals. In what follows, we will study different IC techniques applicable to a CR receiver operating in white, gray, or black spaces. We will show that a CR receiver can adaptively choose its IC strategies to combat interference and enable secondary communications even in black spaces.

spatial distributions of white/gray/black spaces in the presence of a random primary network with homogeneous nodes. There, it was assumed that every active primary transmitter uniquely defines a black and gray space area. As illustrated in Figure 1, the black space area, often considered as the service region, is given by a circular disk with radius L centered at the primary receiver. The gray space area, on the other hand, is an outer ring with radius D surrounding the service region and is

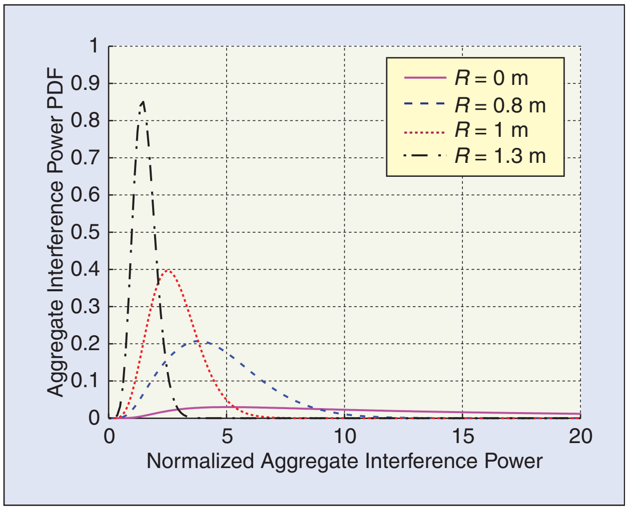

FIGURE 2 PDFs of the aggregate interference power (normalized to the transmit power of the interferers) with different values of the exclusion region radius R (CR transmitter density $\lambda = 1$).

IC at CR Receivers

The aim of introducing IC techniques at a CR receiver is to enable it to successfully operate under higher levels of interference from primary networks. Let us consider a CR receiver operating in a given frequency band. It first performs primary signal sensing and identifies the band as a white, gray, or black space. Based on the sensing results, the CR receiver can then choose to apply corresponding IC techniques to obtain optimized performance. These IC techniques are summarized in Table 1 and will be explained in subsequent sections.

IC for White Spaces

While white spaces are detected, the interference in the frequency band of interest is negligible and can be treated as noise. Therefore, no particular IC technique is needed.

IC for Gray Spaces

The key feature of gray spaces is that the band of interest suffers low- to medium-level interference from primary networks. For this type of interference, it is desirable to use a special type of IC technique called interference suppression, which suppresses the power of primary signals and thereby improves the signal-to-interference-and-noise ratio (SINR) of secondary signals. Interference suppression can be performed by passing the received signal through a filter tailored to the characteristics of the desired secondary signals. These characteristics could be power spectrum, transformed domain features (e.g., wavelet), spatial signatures (e.g., angle of arrival), cyclostationarity, or higher order statistics. Ideally, the signal of interest (SOI) and interfering signal should possess distinct characteristics so that the interference can be easily separated and suppressed.

TABLE 1 *Interference cancelation techniques for cognitive radio networks.*

	Region	Technique
At the CR receiver	White space	No IC needed
	Gray space	Interference suppression
		Filter based
		Transform based
		Receive beamforming
		Cyclostationarity based
		Higher-order statistics based
	Black space	Interference suppression
		Interference cancelation
		Extraction and cancelation
		Reconstruction and cancelation
At the CR transmitter	All regions	Spectrum shaping
		Predistortion filtering
		Spread spectrum
		Transmit beamforming

Filter-Based Approach

Filter-based approaches process signals in the time domain and aim at separating the SOI and interference signals based on their power-spectrum properties. The aim is to synthesize a filter that provides a desired frequency–response function, which enhances regions of the spectrum with high SINR and suppresses those with low SINR. An optimal (Wiener) filter can be derived when the power spectrum (covariance) of the SOI and interference are known. In case the covariance is unknown, adaptive filters can be used to adjust the weights of the filter.

The filter-based approach, especially linear filter, is a matured technology that can be implemented with relatively low complexity. However, since it focuses only on the power spectrum of signals, it cannot suppress cochannel interference or interference with similar waveforms. Therefore, applications of filter-based approach in IC for CR networks are limited.

Transform-Domain Approach

Transform-domain approaches first convert the received signal to the transform domain, remove certain transform components, and then use the inverse transform to synthesize the SOI. For example, an orthogonal frequency-division multiplexing (OFDM) CR receiver can process signals in the frequency domain and remove narrowband interference by excising the interfered subbands. In practice, interference usually cannot be completely removed from the SOI using pure time- or frequency-based processing. Time–frequency analysis then provides a more powerful means for signal separation and classification. Time–frequency representations (TFRs) describe signals in the form of their joint time and frequency characteristics [8]. Widely used time–frequency analysis tools include the short-time Fourier transform (STFT), wavelet, and chirplet. STFT introduces a time-domain window into the Fourier transform and jointly examines the signal properties in both time and frequency domains. The wavelet transform extends the STFT by applying different shapes of window functions in different frequency bands. Chirplet approaches analyze the time–frequency characteristics in a manner that its time–frequency atoms (chirplets) are the rotated versions of STFT or wavelets in the time–frequency plane. TFRs are useful in separating signals with continuously varying frequency content, even when they have overlapping power spectrum.

The transform-domain approach can be used to suppress cochannel interference as long as the SOI and interfering signals have distinct components in the transform domain. A suppression gain of up to 20 dB has been demonstrated in certain OFDM applications [8]. Moreover, only a medium computational load and low hardware complexity are required. The drawback of this approach is that it cannot be applied to cases where the interference has similar waveforms (i.e., same modulation and bandwidth) to the SOI. Nevertheless, in practice, CR can be designed to have dissimilar waveforms to the primary ones. Therefore, the transform-domain approach has great potentials in CR networks if combined with proper waveform design.

Receive Beamforming

In addition to the transform domain, spatial domain can also be exploited to separate the SOI and interference if they have different spatial signatures. This requires a CR receiver to be equipped with multiple antennas to perform beamforming, which applies weights on the antenna array to form a desirable reception pattern. More specifically, when the SOI and interference arrive from different directions, a multiantenna CR receiver can adaptively form different beam patterns to enhance reception in the direction of the SOI and put nulls toward the directions of the interference. In complex propagation environments, a tradeoff is often needed between SOI signal enhancement and interference suppression.

Clearly, beamforming can suppress both the cochannel interference and interference of similar waveforms given favorable propagation conditions. The suppression gain is high given a sufficient number of the antenna elements and the computational complexity is low. However, the hardware cost is high because of the need of using multiple antennas and RF chains. Moreover, the achievable gain is opportunistic since it relies on a favorable propagation condition. Overall, the beamforming approach is a promising candidate for CR base stations and access points. Even for single-antenna CR users, collaborative beamforming can potentially be used to obtain a high-interference suppression gain.

Cyclostationarity-Based Approach

In contrast to stationary signals whose statistical properties are constant over time, cyclostationary signals have statistical properties that vary periodically. Cyclostationarity is evaluated using the spectral correlation density function. It is a much more complete tool for signal analysis than those just relying on the power spectrum, since it provides more information on carrier frequency, data rate, and phase offset. Signals overlap in the power spectrum, or the transform domain can have nonoverlapping features in the cyclic spectrum. In fact, cyclostationarity-based signal detection has been proposed as a main approach for spectrum sensing in CR networks [3]. Using cyclostationarity for signal separation, however, is not as straightforward and requires more research efforts. One established method employing cyclostationarity for signal separation is the frequency shift filter (FRESH) [12], which outputs the weighted sum of frequency-shifted signals. The rationale behind FRESH is that, for many communication signals, certain frequency shifted versions of the signal can be highly correlated with the original signal. This spectral correlation can be exploited to reinforce the SOI and suppress the interference by summing appropriately weighted and frequency-shifted versions of the received signal.

The FRESH gives good performance in suppressing both cochannel interference and interference of similar waveforms. It has been shown that FRESH is effective in suppressing the interference even when it is 10 dB stronger than the SOI [12]. The computation and hardware complexities are also low. The drawback of FRESH is that it requires training to calculate optimal weights of the filter and that the SOI should have a large excess bandwidth. These two requirements, however, can be satisfied in a CR design. Besides FRESH, there exist other methods that exploit the second or higher orders of signal's cyclostationarity. Therefore, the cyclostationarity-based approach has promising applications in CR networks.

Higher Order Statistics-Based Approach

Many signal-processing schemes in communication systems assume that the signals are stationary random processes and can be sufficiently characterized by the mean (first-order statistics) and covariance (second-order statistics). Incorporating higher order statistics, having orders higher than two, into signal processing can provide additional distinction on the SOI and interfering signals [13]. Signal separation using higher order statistics works better when multiple diversity copies of the received signal are available. These diversity copies can be obtained from antenna arrays or, in case of signal antenna systems, from fractionally spaced sampling or oversampling.

Similar to the beamforming and cyclostationarity-based approaches, higher order statistic-based approach can suppress both cochannel interference and interference of similar waveforms. It has been demonstrated that a 17-dB interference suppression gain can be achieved [13]. However, the hardware cost is high because of the need of using multiple antennas or multiple samplers. The computation complexity is also quite demanding. Consequently, we may consider using the higher order statistics-based approach if other approaches with lower complexities fail to achieve a satisfactory performance.

The aforementioned five interference suppression techniques are compared in Table 2 in terms of their capabilities to suppress cochannel interference and interference with similar waveforms, the achievable interference suppression gain, hardware complexity, and computational complexity. In summary, both the transform domain and cyclostationarity-based approaches seem to be promising if proper CR waveforms are used. Moreover, beamforming and higher order statistic-based methods can be used to further improve the IC performance with additional hardware cost.

IC for Black Spaces

Black spaces are usually regarded as unusable for CR users because 1) the potential deployments of primary receivers in the vicinity may prohibit CR transmissions and 2) the high-power interfering primary signals that may block CR receptions. However, the presence of higher power primary signals also means that primary receivers may be able to tolerate higher level of interference from CR networks, making CR transmissions feasible as long as

TABLE 2 Comparison of different interference suppression techniques for CR receivers.

	Filter	Transform	Beamforming	Cyclostationarity	High-Order Statistics
Cochannel interference	No	Yes	Yes	Yes	Yes
Similar waveform	No	No	Yes	Yes	Yes
Suppression gain	Low	High	High	High	High
Hardware complexity	Low	Low	High	Low	High
Computation complexity	Low	Medium	Medium	Medium	High

the interference temperature limit is not violated. On the other hand, a CR receiver can apply proper IC techniques to extract secondary information even when the received signal is dominated by interference from a primary network. Two approaches can be used for IC in black spaces. First, if a CR receiver only has partial information of the interfering signals (e.g., their statistical characteristics), the aforementioned interference suppression techniques can be applied to directly suppress the interference. Second, if a CR receiver has full information of the interfering signals, i.e., the CR receiver is able to accurately estimate/recover the exact waveforms of the interfering signals, it is then desirable to apply a different type of IC technique called interference estimation and cancelation [14], as illustrated in Figure 3.

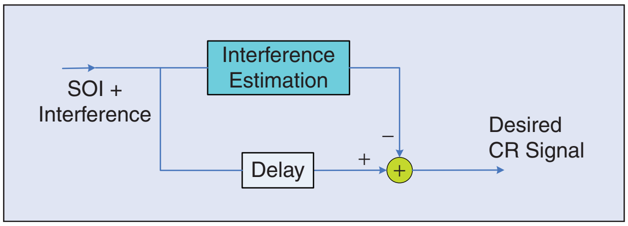

FIGURE 3 Block diagram of a CR receiver using interference estimation and cancelation.

In contrast to the philosophy of interference suppression where the interference is directly suppressed and treated as background noise, the interference estimation and cancelation is performed in two successive steps: 1) estimating the exact interfering signal and 2) subtracting the estimated interference from the received signal. The successive interference cancelation (SIC) algorithm for MUD is based on this very same philosophy. Clearly, the key is to obtain an accurate estimate of the interfering signal before subtraction. There are two approaches for estimating interference: interference extraction and interference reconstruction.

Interference Extraction

Extracting interference from the received signal can be achieved by suppressing the SOIs. Therefore, previously discussed interference suppression techniques can be used to suppress the SOIs and thereby extract the interfering primary signal.

Interference Reconstruction

In the case of digitally modulated primary signals, if a CR receiver receives a strong primary signal and knows its transmission structure (e.g., its coding and modulation schemes), it can first demodulate and decode the primary signal to recover the original primary information bits. Then, the CR receiver can reconstruct the corresponding primary signal based on the knowledge of its transmission structure and channel information.

To further explain the concept of interference reconstruction and cancelation, a simple simulation model was built. In this model, a CR receiver operates in the black space of a terrestrial digital-video broadcasting (DVB-T) system (the primary system). The CR transmission is assumed to be synchronized to an 8-MHz DVB-T channel and applies quadrate phase-shift keying (QPSK) and OFDM for signal modulation. A symbol rate of 6.75 M symbols/s and an OFDM size of 2,048 subcarriers are used. The interfering DVB-T signal is generated by a standard DVB-T transmitter, including both modulation and channel coding. For simplicity, an additive white Gaussian noise (AWGN) channel is assumed. Therefore, the signal received at the CR receiver is the superposition of the CR signal, standard DVB-T signal, and AWGN with unit power. The power of the DVB-T signal is assumed to be dominant. The ratios of the DVB-T signal power and CR signal power to the noise power are referred to as the DVB-T signal-to-noise ratio (SNR) and CR SNR, respectively. The CR receiver applies the aforementioned interference reconstruction and cancelation scheme to cancel DVB-T signals and extract transmitted CR symbols.

On the basis of this simulation model, we investigate the impact of the received CR signal power/SNR and DVB-T signal power/SNR on the symbol error rate (SER) performance of the CR communication link. The simulation results are shown in Figure 4. We can see that, when the power of the CR signal is relatively small, the interfering DVB-T signal can be effectively canceled, and therefore, the SER performance of the CR communication link improves with the increasing power of the CR signal. However, when the CR signal power exceeds a certain threshold, the SER rises very quickly. The reason for this effect is that, when the CR signal power is too strong, it deteriorates the SINR of the DVB signal so that the interference reconstruction

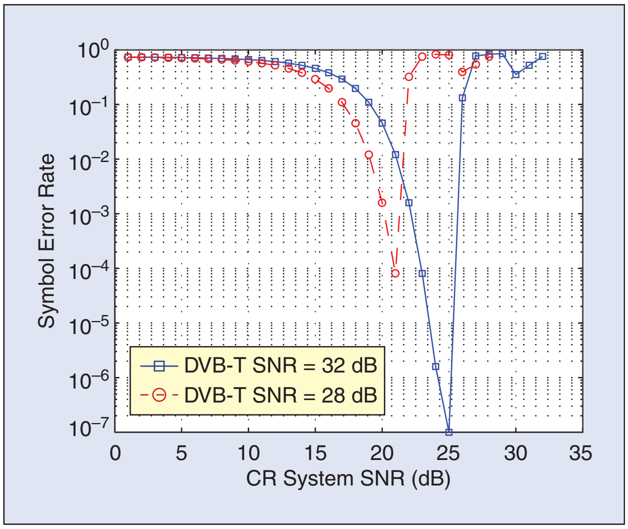

FIGURE 4 Symbol error rate performance of a CR communication link in the presence of high-power interfering DVB-T signals.

becomes erroneous. Therefore, the interfering DVB signal cannot be canceled effectively.

IC at CR Transmitters

In this section, we consider the internetwork interference from CR transmitters to primary receivers. The CR transmissions should be well managed to guarantee that the primary services are not harmfully interfered with. It is therefore important for CR transmitters to adopt certain signal processing schemes, referred to as transmitter-side IC techniques, to mitigate both the cochannel interference and adjacent channel interference (i.e., out-of-band interference) caused to primary receivers. A number of applicable schemes are listed in Table 1 and will be explained in subsequent sections.

Spectrum Shaping

The focus of spectrum shaping, also referred to as pulse shaping, is on generating proper waveforms for secondary signals to minimize the power leakage into the primary bands to be protected. In the literature, spectrum-shaping techniques have been well investigated in the context of ultrawideband (UWB) systems and software-defined radios. The goal is to design adaptive pulse waveforms, which can dynamically react to the spectral environment and produce desired spectral shapes/notches. Preferably, the signal waveforms should be constructed as the linear combination of a limited number of orthogonal basis functions, also known as the core pulse wavelets. These basis functions should be bandwidth limited, time limited, orthogonal to each other, and flexible enough to form any desired shape of the power spectrum. Using orthogonal sinusoid waves as the core pulse wavelets leads to the well-known multicarrier modulation technique. The most popular multicarrier technique is OFDM, which can flexibly mitigate the interference to a particular band by turning off the corresponding subcarriers. However, OFDM wavelets are known to have large side lobes (spectrum leakage), which limit the notch depth to 5–10 dB. Many techniques have been proposed for side-lobe suppression in OFDM systems. For example, an approach called active interference cancelation (AIC) was proposed in [5] to improve the notch performance by nullifying some special tones at the edge of the interference band. Another multicarrier technique is the filter bank-based approach [15], which can generate waveforms with smaller side lobes than OFDM. Besides the multicarrier approaches, nonmulticarrier pulse-shaping techniques use different orthogonal wavelets, such as the prolate spheroidal wave functions, as the basis functions to construct waveforms with desired spectral properties.

Pulse shaping can be used to reduce both the cochannel interference and adjacent channel interference from CR transmitters to primary networks. Typically, a high-suppression gain can be achieved with a medium hardware complexity.

Predistortion Filtering

In practice, one major cause of the adjacent channel interference is the transmission nonlinearity due to cascaded nonlinear components in the RF chain. High linearity is usually required for CR transmitters to ensure minimal interference to primary users. However, high-linearity transmitter chains are not only more expensive but also less power efficient. One way to reduce the linearity requirement is to use predistortion techniques. A predistortion module precompensates the signal entering a nonlinear device for anticipated distortion so that the output from the combined predistortion module and nonlinear device is undistorted [8]. Effective predistortion can be achieved through both analog and digital means. Predistortion filtering is mainly used for suppressing adjacent channel interference. Depending on the degrees of RF signal distortion, it usually provides low to medium suppression gains.

Spread Spectrum

Spread spectrum is a well-known technique that can be used by a CR transmitter to spread the signal energy across a wide bandwidth. The resulted wideband secondary signal would have a low PSD, and therefore, the interference to a particular narrowband primary system can be reduced. An obvious drawback is that more primary systems operating in the wider band can be interfered with. In the context of CR, spread spectrum reduces the cochannel interference at the expense of increasing the interference in adjacent channels. The hardware complexity is low, and high suppression gains (for cochannel interference) are achievable with a large-spreading factor.

Transmit Beamforming

Similar to receive beamforming, transmit beamforming [6] and transmit precoding [7] can be applied to CR networks for mitigating interference to primary systems by adaptively choosing weights on the transmit antenna elements to form an emission pattern with nulls toward the directions of primary receivers. It is an effective and flexible approach to balance between the interference minimization for the primary users and the SINR maximization for the secondary users. Implementations of transmit beamforming are more complicated than receive beamforming since a feedback mechanism is required to inform CR transmitters about the instantaneous channel-state information (CSI). Transmit beamforming is effective in suppressing both the cochannel and adjacent channel interference at the expense of high-hardware costs.

The aforementioned four transmitter-side IC techniques are summarized and compared in terms of their capabilities in canceling cochannel and adjacent channel interference, achievable interference suppression gains, and hardware complexities (Table 3). In summary, spectrum shaping seems to be the most promising method for transmitter IC. The effectiveness of spectrum shaping, however, may rely on a proper predistortion filter to guarantee that the baseband pulse shapes are not distorted in the RF. Besides, transmit beamforming may be of interest to CR base stations, and spread spectrum may be applicable to short-range CR systems to operate in a UWB fashion.

TABLE 3 *Comparison of different IC techniques applicable for CR transmitters.*

	Shaping	Spread	BF	Predistortion
Cochannel interference	Yes	Yes	Yes	No
Adjacent channel interference	Yes	No	Yes	Yes
Suppression gain	High	High	High	Low
Hardware complexity	Medium	Low	High	Low

Other IC Techniques

Decades of research in IC techniques has built a rich literature in this area. In this article, we address only those considered most relevant to internetwork interference cancelation in CR networks. Other types of IC techniques that may also be applicable to CR networks include joint detection/MUD, nonlinear signal processing using neural networks, and analog signal processing [8].

Moreover, previous discussions are restricted to single types of IC techniques. As a natural extension, hybrid IC techniques can be used by combining several simple IC schemes to obtain better performance. A conceptual example of a hybrid IC technique is illustrated in Figure 5, where a CR receiver successively applies beamforming and interference suppression/cancelation to extract desired CR signals. When the primary signal is sufficiently strong, the CR receiver can form a beam toward the primary signal. The enhanced primary signal is then estimated (using either extraction or reconstruction) and subtracted from the received signal. When the primary signal is too weak to be reliably estimated, the CR receiver can form a different beam pattern to enhance the CR signal and nullify the primary signal. The primary signal is then further suppressed using interference-suppression techniques.

Conclusions

CR networks inevitably lead to complex and sophisticated interference scenarios. This has inspired our investigation on applying IC techniques to CR networks with a special focus on mitigating the internetwork interference. We have found that a CR receiver assisted by proper IC techniques can effectively combat interference from primary networks, given that the secondary signals have dissimilar characteristics to those of primary signals. In addition, various IC techniques have been found to be useful for CR transmitters to rigidly control their emission patterns and thereby mitigate the interference caused to primary systems. Moreover, we have shown that hybrid IC schemes can be obtained by combining simple IC techniques. Our investigations have suggested that the performance of CR networks can be significantly improved by using IC technologies.

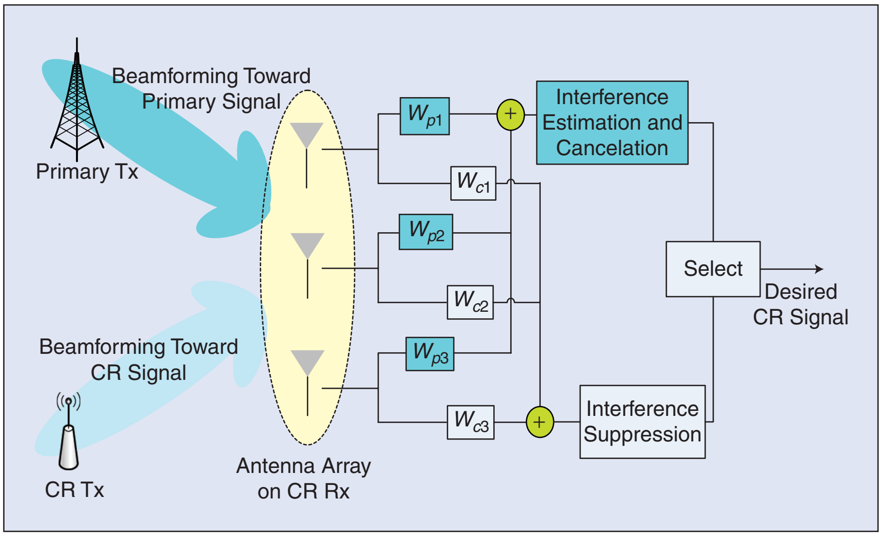

FIGURE 5 A hybrid IC technique combining beamforming and interference cancelation/suppression.

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