Interference Rejection Combining for Black-Space Cognitive Radio Communications

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Abstract. *This paper focuses on multi-antenna interference rejection combing (IRC) based black-space cognitive radio (BS-CR) operation. The idea of BS-CR is to transmit secondary user (SU) signal in the same frequency band with the primary user (PU) such that SU's power spectral density is clearly below that of the PU, and no significant interference is inflicted on the PU receivers. We develop a novel blind IRC technique which allows such operation mode for effective reuse of the PU spectrum for relatively short-distance CR communication. We assume that both the PU system and the BS-CR use orthogonal frequency division multiplexing (OFDM) waveforms with common frame structure. In this case the PU interference on the BS-CR signal is strictly flat-fading at subcarrier level. Sample covariance matrix based IRC adaptation is applied during silent gaps in CR operation. During CR transmission, the target signal detection and channel estimation utilize multiple outputs from the IRC process obtained with linearly independent steering vectors. The performance of the proposed IRC scheme is tested considering terrestrial digital TV broadcasting (DVB-T) as the primary service. The resulting interference suppression capability is evaluated with different PU interference power levels, silent gap durations, and CR device mobilities.*

Keywords: *black-space cognitive radio, underlay cr, interference rejection combining, irc, receiver diversity, ofdm, dvb-t*

1 Introduction

Cognitive radios (CRs) are designed to operate in radio environments with a high level of interference and, at the same time, produce negligible interference to the primary users (PUs) [1]-[3]. CRs have been widely studied in recent years, with main focus on opportunistic white-space operation, i.e., dynamically identifying unused spectral resources for CR operation. Also underlay CR operation has received some attention. Here the idea is to transmit in wide frequency band with low power-spectral density, typically using spread-spectrum techniques [4]. Black space CR (BS-CR), where a CR deliberately transmits simultaneously along the primary signal in the same time-frequency resources without causing objectionable interference has received limited attention [5]-[8]. In general, BS-CR can operate without need for spectrum sensing and requires only limited spectral resources. BS-CR can make very effective reuse of spectrum over short distances.

One of the major requirements for CR operation is to minimize the interference to the primary transmission system. In BS-CR this is reached by setting the CR transmission power at a small-enough level. The most important factor that enables such a radio system is that stronger interference is easier to deal with as compared to weaker interference [9], if proper interference cancellation techniques are utilized. Previous studies from information theory provide theoretically achievable bounds for such cognitive radios [10].

The use of multiple antennas allows for spatio-temporal signal processing, which improves the detection capability of the receiver under fading multipath channel and interference. Various methods of interference cancellation can be found in [11], [12]-[16] and the references therein. For a detector to be optimum under interference, it has to be a multi-user detector [11].

Interference rejection combining (IRC) receivers do not need detailed information about the interfering signals, such as modulation order and radio channel propagation characteristics. Therefore, IRC receivers are simple compared to optimum detectors, making them desirable for CR scenarios.

IRC techniques are widely applied for mitigating co-channel interference, e.g., cellular mobile radio systems like LTE-A [17]. The use of multiple antennas in CRs has been studied earlier, e.g., in [16]. Our initial study on this topic in highly simplified scenario with suboptimal algorithms was in [18], but to the best of our knowledge, IRC has not been applied to BS-CR (or underlay CR) elsewhere. The novel elements of the scheme proposed in this paper include the following:

- The spatial channel of the interfering PU signal does not need to be explicitly estimated, while an initial IRC solution is found by calculating the sample covariance matrix during a silent gap in CR transmission.
- The channel of the target CR transmission is estimated for the maximum number of linearly independent signals from which the PU interference has been suppressed.
- The IRC weights are obtained from the channel estimates and initial IRC solution through maximum ratio combining (MRC) of the linearly independent signal set.

In this paper we consider BS-CR operation in the terrestrial TV frequency band, utilizing a channel with an on-going relatively strong TV transmission. The PU is assumed to be active continuously. If the TV channel becomes inactive, this can be easily detected by each of the CR stations in the reception mode. Then the CR system may, for example, continue operation as a spectrum sensing based CR system. In our case study, we focus on the basic scenario of IRC based multi-antenna CR receiver with co-channel interference generated by a single PU transmitter. The performance of such a system under different interference levels, timing offsets, and modulation orders is studied. Also, the effect of silent period length and CR device mobility on the performance is evaluated. The rest of the paper is organized as follows: In Section 2, the BS-SC scenario and proposed IRC scheme are explained. The system model and IRC solution are formulated in Section 3. Section 4 presents the simulation setup and performance evaluation results. Finally, concluding remarks are presented Section 5.

2 IRC-Based Black-Space Cognitive Radio Scenario

In our basic scenario, illustrated in Fig. 1, we consider a CR receiver using multiple antennas to receive data from a single-antenna cognitive transmitter. The CR operates within the frequency band of the PU, and the PU power spectral density (PSD) is very high in comparison to that of the CR. The primary transmission is assumed to be always present when the CR system is operating. The primary transmitter generates a lot of interference to the CR transmission, which operates closer to the noise floor of the primary receiver, and due to this, the primary communication link is protected. We consider frequency reuse over relatively small distances, such as an indoor CR system. The multi-antenna configuration studied here is that of single-input multiple output (SIMO). Other configurations, involving also transmit diversity in the CR link are also possible, but they are left as a topic for future studies.

Here the PU is a cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) based DVB-T system [19]. The CR system is also an OFDM based multicarrier system using the same subcarrier spacing and CP length as the primary system. Thus, it has the same overall symbol duration. The CR system is assumed to be synchronized to the primary system in frequency and in quasi-synchronous manner also in time. The CP length is assumed to be sufficient to absorb the channel delay spread together with the residual offsets between the two systems observed at the CR receiver. Consequently, the subcarrier-level flat-fading circular convolution model for spatio-temporal channel effects applies to the target CR signal and to the PU interference signal as well. Then the IRC process can be applied individually for each subcarrier. Since the CR receiver observes the PU signal at very high SINR level, synchronization task is not particularly difficult and low-complexity algorithms can be utilized. Considering short-range CR scenarios, the delay spread of the CR channel has a minor effect on the overall channel delay spread to be handled in the time alignment of the two systems. Basically, if all CR stations are synchronized to the PU, they are also synchronized with each other.

Both the primary and the CR systems use QAM subcarrier modulation, but usually with different modulation orders. The received CR signal consists of contributions from both the desired CR communication signal and the primary transmission signal, the latter one constituting a strong interference. Our proposed scheme includes two phases in the CR system operation:

1. During the first phase, the CR transmission is stopped (silent gap) and the IRC process is adapted blindly to minimize the energy of combined signal during the silent period. This is done individually for each subcarrier. Since the target channel is not available during this stage, IRC solutions are found for the maximum number of linearly independent (virtual) steering vectors. During the CR reception phase, the corresponding IRC output signals are used for channel estimation and data detection. They are referred to as partial IRC signals.
2. During the second phase, the CR system is operating. The CR channel coefficients are estimated for each partial IRC signal using training symbols (containing reference symbols in all subcarriers). For data symbols, the partial

IRC signals are combined using maximum ratio combining (MRC) based on the estimated channel coefficients.

This two-phase process is straightforward to implement and it is able to track the channel fading with relatively low mobility. In future work, it is worth to consider adaptation of the IRC process without silent gaps after the first one required for the initial solution. This would help to reduce the related overhead in throughput.

No explicit channel estimation of the PU channel is required in this approach. The CR channel is estimated from the partial IRC signals, from which the PU interference has been effectively suppressed.

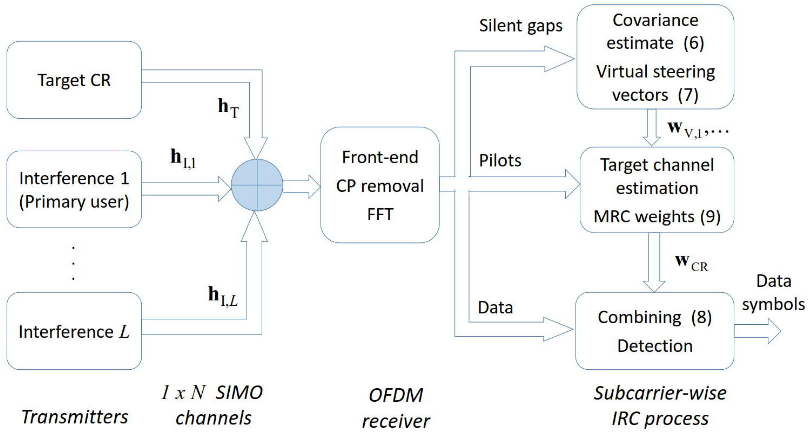

Fig. 1. Blackspace CR system model.

3 IRC for Black-Space Cognitive Radio

Following the quasi-synchronous OFDM system model explained in the previous section, the detection process at the CR receiver can be formulated at OFDM subcarrier symbol level as a flat-fading process. For the $1 \times N$ SIMO antenna configuration of the CR transmission link and L interfering signals, the received signal can be expressed as

$$\mathbf{r} = \mathbf{h}_\mathrm{T} x_\mathrm{T} + \sum\nolimits_{l=1}^{L} \mathbf{h}_{\mathrm{I},l}\, x_{\mathrm{I},l} + \boldsymbol{\eta} . \tag{1}$$

Here $\mathbf{h}_\mathrm{T} \in \mathbb{C}^{N\times 1}$ is the channel gain vector for the target CR transmission, $\mathbf{h}_{\mathrm{I},l} \in \mathbb{C}^{N\times 1}$ is the spatial channel from the lth interferer to the CR receiver, x_T and $x_{\mathrm{I},l}$ are the corresponding transmitted subcarrier symbols, and $\boldsymbol{\eta} \in \mathbb{C}^{N\times 1}$ is spatially white additive white Gaussian noise (AWGN). Naturally, during silent gaps of CR operation, the first term of (1) is missing. For detection, the signals from different antennas are weighted and combined using a linear combiner. This can be expressed as the inner product

$$y = \mathbf{w}^\mathrm{H} \mathbf{r} , \tag{2}$$

where $\mathbf{w} \in \mathbb{C}^{N\times 1}$ is the combiner weight vector, and H stands for Hermitian (complex-conjugate transpose). Finding the optimum weight vector is an optimization problem. Generally, the linear minimum mean-squared error (LMMSE) solution minimizes the mean-squared error in the target signal x_T,

$$J = E\left[\left|x_\mathrm{T} - \mathbf{w}^\mathrm{H}\mathbf{r}\right|^2\right] . \tag{3}$$

In interference rejection combining (IRC) we assume knowledge of the covariance matrix of the interferences. If the channels from the interferers to the CR receiver antenna array are known, the noise plus interference covariance matrix can be expressed as

$$\mathbf{\Sigma}_\mathrm{NI} = \sum\nolimits_{l=1}^{L} P_l \mathbf{h}_{\mathrm{I},l} \mathbf{h}_{\mathrm{I},l}^\mathrm{H} + P_\mathrm{N}\mathbf{I} . \tag{4}$$

Here $P_{\mathrm{I},l}$ is the power of interferer l, P_N is the noise power, and $\mathbf{I}$ is the identity matrix of size N. Then the well-known LMMSE solution [20] is

$$\mathbf{w} = \mathbf{\Sigma}_\mathrm{NI}^{-1}\mathbf{h}_\mathrm{T}\left(\mathbf{h}_\mathrm{T}^\mathrm{H}\mathbf{\Sigma}_\mathrm{NI}^{-1}\mathbf{h}_\mathrm{T} + 1/P_\mathrm{T}\right)^{-1} , \tag{5}$$

where P_T is the target CR signal power.

Estimating the interferer channel vector would increase the complexity of the CR receiver, even in the single interferer case of our basic scenario. In case of multiple interferers, e.g., from other BS-CR systems operating nearby, this would be quite challenging. Therefore, we use the sample covariance matrix of the received signal,

$$\bar{\mathbf{\Sigma}}_\mathrm{NI} = \sum\nolimits_{m=1}^{M} \mathbf{r}(m)\mathbf{r}(m)^\mathrm{H} \tag{6}$$

during the silent gap of the CR transmission as the estimate of $\mathbf{\Sigma}_\mathrm{NI}$. Here m is the OFDM symbol index and M is the length of the estimation period (i.e., silent gap length) in OFDM symbols.

In the proposed scheme it is not possible to estimate the CR channel before the interference cancellation stage. Therefore, during CR operation phase 1, we carry out the IRC adaptation process for N orthogonal virtual steering vectors, resulting in N weight vectors $\mathbf{w}_{\mathrm{V},1}, \mathbf{w}_{\mathrm{V},2}, \ldots, \mathbf{w}_{\mathrm{V},N}$. We use the unit vectors $\mathbf{h}_{\mathrm{V},1} = [1,0,0,\ldots,0]^\mathrm{T}$, $\mathbf{h}_{\mathrm{V},2} = [0,1,0,\ldots,0]^\mathrm{T}, \ldots, \mathbf{h}_{\mathrm{V},N} = [0,0,0,\ldots,1]^\mathrm{T}$ as the virtual steering vectors for simplicity. Furthermore, instead of the scaling of (5), the weight vectors are scaled to have unit Euclidean norm,

$$\mathbf{w}_{\mathrm{V},n} = \bar{\mathbf{\Sigma}}_\mathrm{NI}^{-1}\mathbf{h}_{\mathrm{V},n} \Big/ \left\|\bar{\mathbf{\Sigma}}_\mathrm{NI}^{-1}\mathbf{h}_{\mathrm{V},n}\right\| . \tag{7}$$

This results in unit noise variance for the corresponding weighted output signals $y_n = \mathbf{w}_{\mathrm{V},n}^\mathrm{H}\mathbf{r}, n = 1,2,\ldots,N$, which is essential for the following maximum ratio combining (MRC) stage. The outputs y_n are different observations of the target signal, for which the interference cancellation has been applied. When the number of receiver antennas is higher than the number of interference sources, there is diversity in these observations, and diversity combining can be used for enhancing the performance. Among the linear combination methods, MRC maximizes the signal to interference-plus-noise ratio of the combined signal.

During the second CR operation phase, data symbols are transmitted, along with training symbols at regular intervals. For each training symbol (containing reference symbols in all active subcarriers), the N channel coefficients $\hat{h}_{\mathrm{V},1}, \hat{h}_{\mathrm{V},2}, \ldots, \hat{h}_{\mathrm{V},N}$ are first estimated for each of the effective channels corresponding to the N observations as $\hat{h}_{\mathrm{V},n} = \mathbf{w}_{\mathrm{V},n}^{\mathrm{H}} \cdot \mathbf{r} / p$, where p is the transmitted pilot symbol value. Then the data symbol estimate is obtained by maximum ratio combining the N samples obtained by applying the virtual steering vectors,

$$\hat{d} = \mathbf{w}_{\mathrm{MRC}}^{\mathrm{H}} \cdot \left[\mathbf{w}_{\mathrm{V},1}\ \mathbf{w}_{\mathrm{V},2} \cdots \mathbf{w}_{\mathrm{V},N} \right]^{\mathrm{H}} \cdot \mathbf{r} \ , \tag{8}$$

where the MRC weights are given by

$$\mathbf{w}_{\mathrm{MRC}} = [\hat{h}_{\mathrm{V},1}\, \hat{h}_{\mathrm{V},2} \ldots \hat{h}_{\mathrm{V},N}]^{\mathrm{T}} \Big/ \sqrt{\sum_{k=1}^{N} \left| \hat{h}_{\mathrm{V},k} \right|^2} \ . \tag{9}$$

The effective weight vector becomes

$$\begin{aligned} \mathbf{w}_{\mathrm{CR}} &= \left[\mathbf{w}_{\mathrm{V},1}\ \mathbf{w}_{\mathrm{V},2} \cdots \mathbf{w}_{\mathrm{V},N} \right] \cdot \mathbf{w}_{\mathrm{MRC}} \\ &= \sum_{n=1}^{N} \hat{h}_{\mathrm{V},n} \mathbf{w}_{\mathrm{V},n} \Big/ \sqrt{\sum_{k=1}^{N} \left| \hat{h}_{\mathrm{V},k} \right|^2} \ . \end{aligned} \tag{10}$$

We can see that for data symbol detection with stationary channels, we just need to calculate and use this weight vector, instead of applying the MRC weights on the samples obtained by the weight vectors $\mathbf{w}_{\mathrm{V},n}$.

This model indicates various options for dealing with channel fading. Generally, the PU channel should not vary significantly between the silent periods. The most critical scenario in this respect is a moving CR receiver, which causes also the PU channel to be time varying. Due to the strong PU interference, the interference cancellation process is sensitive to the resulting errors in the channel covariance estimate. For slowly-fading CR channels, it is enough to calculate the effective weights for each training symbol and use the same weights until the next training symbol. With higher mobility, the effective weights can be interpolated between consecutive training symbols. The effect of mobility is investigated through simulations in the following section.

4 Performance Evaluation

The simulations are carried out for the system setup explained in Section 2. The carrier frequencies of CR and PU are the same and it is here set to 700 MHz, which is close to the upper edge of the terrestrial TV frequency band. The modulation order used by CR varies between 4QAM, 16QAM, and 64QAM. The pilot symbols are binary and have the same power level as the data symbols. The primary transmitter signal follows the DVB-T model with 16QAM modulation, 8 MHz bandwidth, and CP length of 1/8 times the useful symbol duration, i.e., 28 µs. The IFFT/FFT length is 2048 for both systems. The DVB-T and CR systems use 1705 and 1200 active subcarriers, respectively. ITU-R Vehicular A channel model (about 2.5 µs delay spread) is used for the CR system and Hilly Terrain channel model (about 18 µs delay spread) for PU transmission. The CR receiver is assumed to have four antennas, and uncorrelated 1x4 SIMO configurations are used for both the primary signal and the CR signal.

The number of spatial channel realizations simulated in these experiments is 500. The ratio of CR and PU signal power levels at the CR receiver (referred to as the signal to interference ratio, SIR) is varied. The lengths of the OFDM symbol frame and silent gap for interference covariance matrix estimation are also varied (expressed in terms of CP-OFDM symbol durations). The training symbol spacing is 8 OFDM symbols, and the frame length is selected in such a way that training symbols appear as the first and last symbol of each frame, along with other positions. Channel estimation uses linear interpolation between the training symbols.

Fig. 2 shows a basic bit error-rate (BER) vs. SNR simulation result with 4QAM (QPSK) and 64QAM modulations and SIR values of -10, -20, and -30 dB. Also the interference-free baseline case (SIR=100 dB) is included. The CR block length is 41 OFDM symbols (6 training symbols and 35 data symbols), and the interference covariance estimation is based on a silent gap of 32 OFDM symbols. In this case, the interference covariance estimate is very good, and IRC performs very well. The effect of the interference power is relatively small: reducing the SIR from -10 dB to -30 dB, the performace loss at 1 % BER level is about 0.6 dB for QPSK and about 1.7 dB for 64QAM. When comparing the BS-CR performance with the interference-free case, the loss is about 3.5 dB for both QPSK and 64QAM at 1 % BER level and -30 dB SIR.

Next we consider the performance with slowly-fading channels. It was found also experimentally that the case where the CR transmitter is moving but CR receiver is stationary is much easier to handle, because the interference covariance matrix is stationary as long as the PU and CR receiver are stationary. Therefore, we focus on the case where the CR receiver is moving, while the CR transmitter is stationary, and both the target CR channel and the interference are fading with the same mobility, 3 km/h. Figs. 3 and 4 show both the effect of the silent gap length and the OFDM frame length on the performance. We can notice that by placing the silent gap in the middle of the frame and using the interference covariance estimate for detecting both the preceding and following OFDM symbols, the CR frame length could be doubled without performance loss. However, this is not assumed in Figs. 3 and 4, because it would require extensive data buffering on the receiver side. In this simulation set-up, the best length for the silent gap is about 32 OFDM symbols. Generally, while acceptable CR link performance can still be achieved, significant performance loss is observed with respect to the stationary case. Also the feasible CR frame length is rather limited, leading to relatively high overhead due to the silent gaps. The performace loss with 3 km/h mobility is about 4.7 dB and 10 dB with the the frame lengths of 17 and 41 OFDM symbols, respectively, compared to the stationary case.

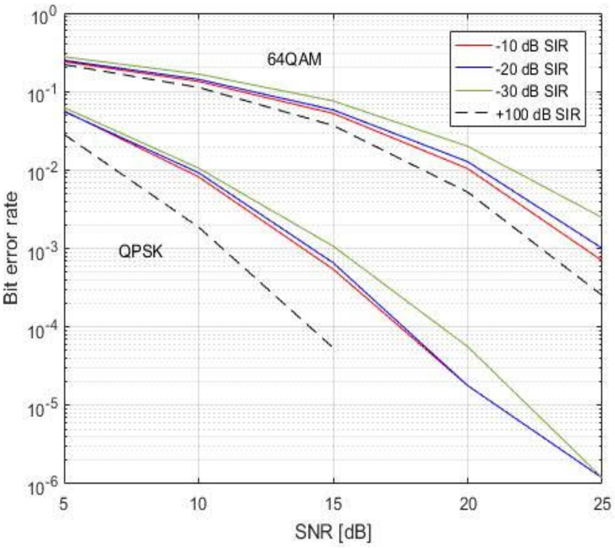

Fig. 2. Performance QPSK and 64QAM systems with stationary channel, silent gap duration of 32 symbols, and OFDM frame length of 41 symbols.

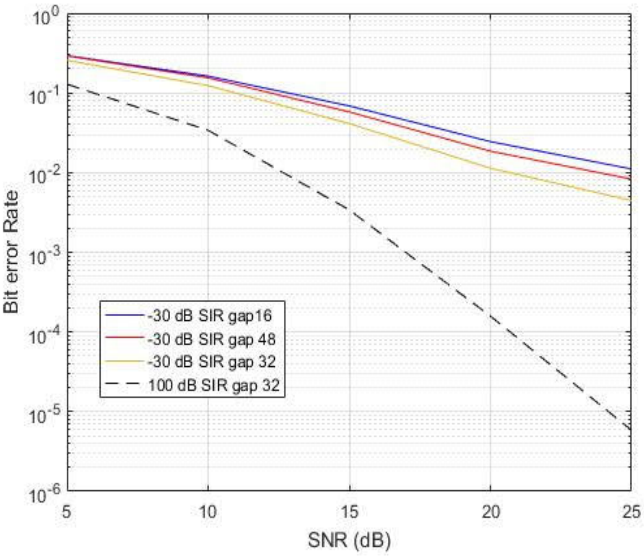

Fig. 3. Performance of a 16QAM system with 3 km/h mobility, 700 MHz carrier frequency, OFDM frame length of 17 symbols, with various gaps and SIR= -30 dB.

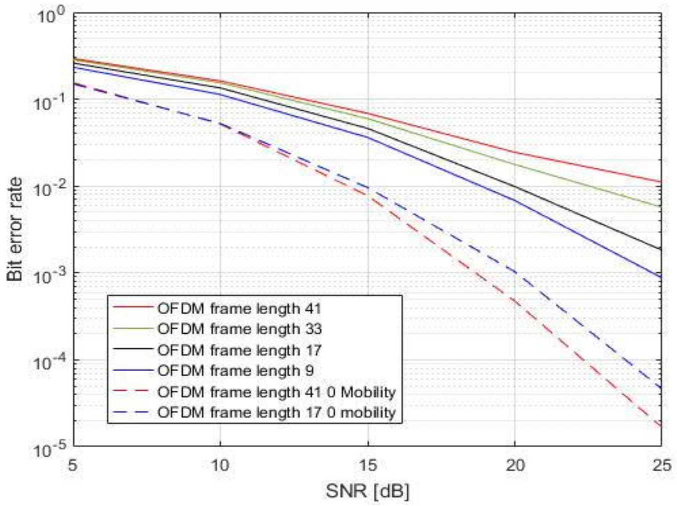

Fig. 4. Performance for a 16QAM system with 3 km/h mobility, 700 MHz carrier frequency, silent gap of 32 symbols, and SIR= -30 dB.

5 Conclusion

The performance of cognitive transmission links in the presence of strong interferences in the black-space CR scenario was investigated. The interference rejection capability of IRC using multiple receive antennas for various modulation orders was studied. It was found that the IRC performs very well in the basic SIMO-type BS-CR scenario when stationary channel model is applicable, e.g., in fixed wireless broadband scenarios. However, the scheme is rather sensitive to the fading of the PU channel. Due to the strong interference level, the interference cancellation process is affected by relatively small errors in the covariance matrix estimate. For covariance estimation, the silent gap length should be in the order of 32 OFDM symbols, and the CR OFDM frame length should be of the same order or less, even with 3 km/h mobility. This leads to high overhead due to the silent gaps.

In future work, it is worth to consider adaptation of the IRC process without silent gaps after the first one required for the initial solution. This would help to reduce the related overhead in throughput. One possible approach is to do this in a decision-directed manner: first estimating the covariance matrix in the presence of the target signal and then cancelling its effect based on detected symbols and estimated target channel.

In the basic TV black-space scenario, there is only one strong TV signal present in the channel, in agreement with our assumption about the primary interference sources. DVB-T system allows also single-frequency network (SFN) operation and the use of repeaters to improve local coverage. In both cases, the primary transmissions can be seen as a single transmission, with a spatial channel that depends on the specific transmission scenario, and the proposed scheme is still applicable.

The scheme can also be extended to scenarios where multiple CR systems are operating in the same region. If all CR systems are time-synchronized to the PU and they are at a relatively small distance from each other, they are also synchronized with each other, and could be handled by the IRC process as an additional interference source following the model of Eq. (1). In future studies, also the effect of antenna correlation will be taken into consideration. The complexity reduction of the IRC receiver with larger number of antennas is also an interesting topic for further studies.

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