Interpolation-Based Interference Rejection Combining for Black-Space Cognitive Radio in Time-Varying Channels

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Abstract. In this paper, we investigate multi-antenna interference rejection combing (IRC) based black-space cognitive radio (BS-CR) operation in time-varying channels. 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 explore the effects of interpolation and mobility on the 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 numerology. 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. We propose an interpolation-based scheme for tracking the spatial covariance in time-varying channels, demonstrating significantly improved robustness compared to the earlier scheme. 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, data block lengths, and CR device mobilities.

Keywords: Black-space cognitive radio · Underlay CR · IRC · Interference rejection combining · Multi-antenna system · Receiver diversity · Mobility · OFDM · DVB-T

1 Introduction

Cognitive radios (CRs) are intended to operate in radio environments with a high level of interference and, simultaneously, produce negligible interference to the primary users (PUs) [1–3]. CR studies in the past have been focusing on opportunistic whitespace scenarios where the unused spectrum is dynamically identified and used. 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

A. Kliks et al. (Eds.): CrownCom 2019, LNICST 291, pp. 168–179, 2019.
https://doi.org/10.1007/978-3-030-25748-4_13

simultaneously along the primary signal in the same time-frequency resources without causing objectionable interference has received limited attention [5–8]. BS-CR systems effectively reuse the spectrum over short distances. It can operate with limited spectrum resources and can be used without any additional spectrum sensing.

As discussed in our previous paper [9], 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 [10], if proper interference cancellation techniques are utilized. Previous studies from information theory provide theoretically achievable bounds for such cognitive radios [11].

Multi-antenna systems allow for spatio-temporal signal processing, which do not only improve the detection capability of the receiver but also improve performance in fading multipath channels with interference. Various methods of interference cancellation can be found in [12–17] and the references therein. All other detection algorithms except the multi-user detector perform sub-optimally [12].

The interference rejection combining (IRC) receivers have the significant advantage in comparison to the other receivers in multi-user scenarios that they do not need detailed information about the interfering signals, such as modulation order and radio channel propagation characteristics. For CR scenarios, IRC receivers in general are simple and desirable compared to optimum detectors. IRC techniques are widely applied for mitigating co-channel interference, e.g., in cellular mobile radio systems like LTE-A [18]. The use of multiple antennas in CRs has been studied earlier, e.g., in [17]. Our initial study on this topic in highly simplified scenario with suboptimal algorithms was in [19], but to the best of our knowledge, IRC has not been applied to BS-CR (or underlay CR) elsewhere. In this current study we develop the ideas that we presented in [9] under more practical situations and study the performance of our algorithms in more details. Notably, the scheme studied in [9] was found to be very sensitive to mobility, because its performance is critically affected by errors in spatial covariance estimation. Here in this work we extent our previous studies on the effects of mobility and propose a scheme to improve the quality of the covariance estimation with time-varying channels using interpolation between sample covariance-based estimates.

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, mobilities, frame structures, and modulation orders is studied, and the improved robustness obtained through covariance interpolation is highlighted.

The rest of the paper is organized as follows: In Sect. 2, the BS-SC scenario and proposed IRC scheme are explained. The system model and IRC solution are formulated in Sect. 3. Section 4 presents the simulation setup and performance evaluation results. Finally, concluding remarks are presented Sect. 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.

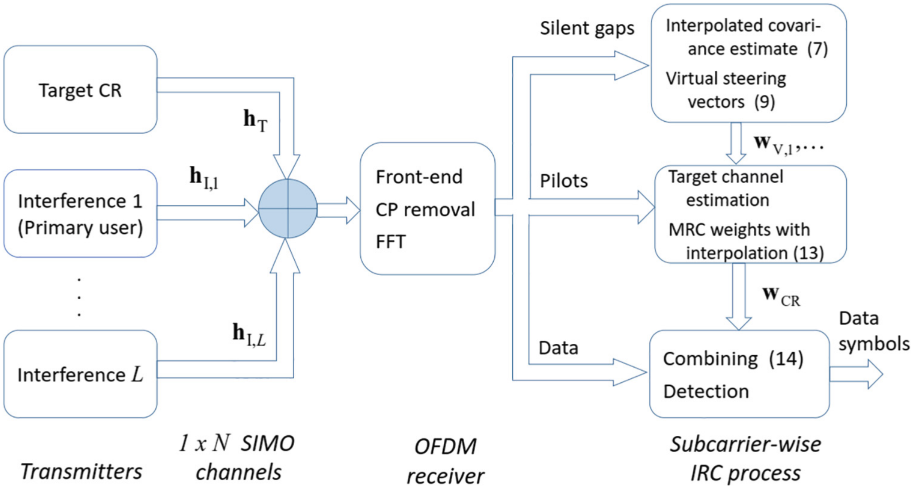

Fig. 1. Modified black-space CR system mode with silent gap interpolation. The related equation numbers are indicated.

Here the PU is a cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) based DVB-T system [20]. The CR system is also an OFDM based multi-carrier 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. In addition to these, we assume that the secondary user is mobile within a given range and the effects of mobility on the system performance are studied.

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 as described in our previous work [9]. The spatial characteristics of the PU interference are modeled using multiantenna sample covariance matrix, which is estimated during silent gaps in the CR transmission, independently for each active subcarrier. No explicit channel estimation of the PU channel is required. The CR channel is estimated from the partial IRC signals, from which the PU interference has been effectively suppressed.

In this work we study how channel fading with mobility affects the performance. We consider adaptation of the IRC process using interpolation of the sample covariance matrices between the silent gaps. This is expected to improve the performance, allowing to increase the data block length between silent gaps, thus reducing the related overhead in throughput.

3 IRC for Black-Space Cognitive Radio

Based on the OFDM model mentioned above, subcarrier-wise detection is considered with flat-fading process to get rid of the challenge of frequency selectivity in the IRC process.

In the SIMO configuration, the CR is assumed to have N receiver antennas and L different interference sources are assumed. Based on this model, the signal received by the CR can be formulated for each active subcarrier as follows:

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

Here x_{T} is a transmitted subcarrier symbol and $\mathbf{h}_{\mathrm{T}}$ is the target channel vector with N receiver antennas in the CR, $x_{\mathrm{I},l}$ is the lth interfering signal, and $\mathbf{h}_{\mathrm{I},l}$ is the channel vector for the lth interferer. Finally, $\boldsymbol{\eta}$ is the additive white Gaussian noise (AWGN) vector. In this generic system model, it is assumed that the PU is the dominant interferer, and the other interference sources are, e.g., other CR systems introducing co-channel interference at relatively low power level.

3.1 Stage 1: Covariance Matrix Estimation and IRC Process

As it is illustrated in Fig. 1, the interference minimizing IRC weights are obtained during the silent period. Due to that, Eq. (1) can be modified during silent gaps of CR operation as

$$\mathbf{r} = \sum\nolimits_{l=1}^{L} \mathbf{h}_{\mathrm{I},l} x_{\mathrm{I},l} + \boldsymbol{\eta}. \tag{2}$$

Here it is assumed that only interference and noise are present during the silent period in the signal observed by the CR. Linear combiner is used for the signals from different antennas with a weight process in detection as follows:

$$y = \mathbf{w}^{\mathrm{H}}\mathbf{r}, \tag{3}$$

where y is the detected signal, $\mathbf{w}$ is the weight vector with N elements, and superscript H denotes the Hermitian (complex-conjugate transpose).

Determining the optimum weight values is an optimization problem which can be solved with the linear minimum mean-squared error (LMMSE) criterion [21] that aims to minimize the mean-squared error with respect to the target signal x_{T},

$$J = E\left[\left|x_{\mathrm{T}} - \mathbf{w}^{\mathrm{H}}\mathbf{r}\right|^{2}\right]. \tag{4}$$

When knowledge of the covariance matrix is calculated/known, interference rejection combining (IRC) can be applied. For the covariance matrix, two cases can be considered: (i) perfect channel state information and (ii) sample covariance based approaches.

Perfect Channel Information Case

Assuming that the channel vectors form the interferers are perfectly known, the noise plus interference covariance matrix can be calculated as

$$\boldsymbol{\Sigma}_{\mathrm{NI}} = \sum\nolimits_{l=1}^{L} P_l \mathbf{h}_{\mathrm{I},l} \mathbf{h}_{\mathrm{I},l}^{\mathrm{H}} + P_{\mathrm{N}}\mathbf{I}, \tag{5}$$

where P_l is the variance of interferer l, P_{N} is the noise variance that can be obtained from the SNR and $\mathbf{I}$ is the identity matrix of size NxN. Assuming that the channel vector for the target signal is known, the conventional LMMSE solution for the weight vector is

$$\mathbf{w} = \boldsymbol{\Sigma}_{\mathrm{NI}}^{-1}\mathbf{h}_{\mathrm{T}}\left(\mathbf{h}_{\mathrm{T}}^{\mathrm{H}}\boldsymbol{\Sigma}_{\mathrm{NI}}^{-1}\mathbf{h}_{\mathrm{T}} + 1/P_{\mathrm{T}}\right)^{-1} \tag{6}$$

where P_{T} is the target CR signal power and unit noise variance is assumed.

In the BS-CR scenario with a single dominant interferer, the estimation of the PU channel is relatively straightforward if the CR knows PUs pilot structure. However, in case of multiple interferers, the channel vectors of all interferers should be estimated, which becomes quite challenging. Furthermore, the target channel cannot be estimated before the interference cancellation. Therefore, the perfect channel information case serves mainly as an ideal reference in performance comparisons.

Sample Covariance Based Case Without PU Channel Information

It is difficult to have the prefect channel state information on the CR receiver side. Alternatively, the joint interference and noise covariance matrix can be estimated by the sample covariance matrix of the received signal in the absence of the target transmission, i.e., during the silent gaps as

$$\bar{\Sigma}_{\mathrm{NI}} = \sum\nolimits_{m=1}^{M} \mathbf{r}(m)\mathbf{r}(m)^{\mathrm{H}}. \tag{7}$$

Here m is the OFDM symbol index and M is the observation length in subcarrier samples, which is chosen equal to the length of the silent gap.

Linear Interpolation for Interference Covariance Tracking with Mobility

Regarding the mobility aspects, there are significant differences in the effects of PU transmitter mobility, CR transmitter mobility, and CR receiver mobility. If the PU transmitter is stationary and CR receiver is stationary, the mobility of CR transmitter is easier to handle, because the dominating PU interference is stationary, and the variations in the noise and interference covariance matrix are only due to the co-channel CR interferes. However, even in this case, radio environment of the CR receiver may vary due to movement of people or vehicles nearby. Therefore, some tolerance to mobility is required also in such scenarios, at least with pedestrian mobilities. The mobility of PU transmitter or CR receiver make the dominant interference time-varying, and in the BS-CR scenario, the CR link performance is very sensitive to quality of the PU interference covariance matrix estimate. Therefore, it is important to investigate these mobility effects and consider enhanced schemes for tracking the interference covariance with mobility.

While considering the sample covariance-based approach, we assume that the fading effect during each silent gap is small enough to be neglected. Then we apply linear interpolation for the covariance matrix elements when calculating the weight vectors for the data symbols between two consecutive silent gaps.

There are two key parameters in this process, the silent gap length and the data block length between two consecutive gaps. Increasing the gap length improves the performance with low mobility but degrades the performance with higher mobility and increases the overhead in throughput. Increasing the data block length increases the throughput but degrades the performance with mobility. These tradeoffs are investigated through simulations in Sect. 4 of this paper.

IRC Process

As indicated in the model shown in Fig. 1, the CR channel cannot be estimated before the step of the interference cancellation. Hence, we apply the IRC process with N orthogonal virtual steering vectors. For this operation, following unit vectors are applied as the virtual steering vectors,

$$\begin{array}{c} \mathbf{h}_{\mathrm{V},1} = [1,\,0,\,0,\,0,\ldots,\,0]^{\mathrm{T}} \\ \mathbf{h}_{\mathrm{V},2} = [0,\,1,\,0,0,\,\ldots,\,0]^{\mathrm{T}} \\ \cdots \\ \mathbf{h}_{\mathrm{V},N} = [0,\,0,\,0,0,\,\ldots,\,1]^{\mathrm{T}} \end{array}. \tag{8}$$

The obtained weight vectors are normalized as follows:

$$\mathbf{w}_{\mathrm{V},n} = \bar{\Sigma}_{\mathrm{NI}}^{-1}\mathbf{h}_{\mathrm{V},n} \Big/ \left\| \bar{\Sigma}_{\mathrm{NI}}^{-1}\mathbf{h}_{\mathrm{V},n} \right\|. \tag{9}$$

In this case the weighted output signals

$$y_n = \mathbf{w}_{\mathrm{V},n}^{\mathrm{H}}\,\mathbf{r}, \qquad n = 1, 2, \ldots, N \tag{10}$$

have equal noise variances. This normalization provides optimum performance for the following maximum ratio combining (MRC) stage.

3.2 Stage 2: Target Channel Estimation with Linear Interpolation and MRC Combining

In the second stage, data symbols of the CR link are transmitted together with the training/pilot symbols. The IRC process targets to cancel the interference from all of the weighted output signals, while the MRC stage combines these signals with maximum SNR at the output. The N channel coefficients for the weighted output signals can be estimated using the pilot symbols as follows:

$$\hat{h}_{\mathrm{V},n} = y_n/p = \mathbf{w}_{\mathrm{V},n}^{\mathrm{H}} \cdot \mathbf{r}/p, \qquad n = 1, 2, \ldots, N, \tag{11}$$

where p is the transmitted pilot symbol value.

Linear Interpolation for Channel Estimation
In the traditional pilot-based channel estimation process, it is required to use efficient interpolation techniques, such as linear interpolation or quadratic interpolation, based on the channel information at pilot sub-carrier symbols. The performance of linear interpolation technique is better than the piecewise-constant interpolation methods [22, 23]. Due to that, linear interpolation is considered in our study due to its simplicity. Generally, with a 2D pilot structure, the channel estimate for a data symbol is obtained by 2D linear interpolation between the three closet pilot symbols in time and frequency. The MRC weights for a data symbol are then calculated as

$$\mathbf{w}_{\mathrm{MRC}} = \left[\hat{h}_{\mathrm{V},1}\, \hat{h}_{\mathrm{V},2} \ldots \hat{h}_{\mathrm{V},N}\right]^{\mathrm{T}} \Big/ \sqrt{\sum\nolimits_{k=1}^{N} \left|\hat{h}_{\mathrm{V},k}\right|^{2}}, \tag{12}$$

where $\hat{h}_{\mathrm{V},n}$, $n = 1, \ldots, N$, denote the corresponding interpolated channel estimates.

3.3 Stage 3: Combining for Detection

After the MRC weights are calculated, the effective weight vectors for CR can be obtained as,

$$\begin{aligned}\mathbf{w}_{\mathrm{CR}} &= \left[\mathbf{w}_{\mathrm{V},1}\ \mathbf{w}_{\mathrm{V},2}\ \cdots\ \mathbf{w}_{\mathrm{V},N}\right]\cdot\mathbf{w}_{\mathrm{MRC}} \\ &= \sum\nolimits_{n=1}^{N}\hat{h}_{\mathrm{V},n}\mathbf{w}_{\mathrm{V},n}\Bigg/\sqrt{\sum\nolimits_{k=1}^{N}\left|\hat{h}_{\mathrm{V},k}\right|^{2}}.\end{aligned} \tag{13}$$

In the final stage, the equalized data symbols are calculated by maximum ratio combining the N samples obtained by applying the virtual steering vectors,

$$\hat{d} = \mathbf{w}_{CR}^{\mathrm{H}}\cdot\mathbf{r}. \tag{14}$$

It is enough to calculate and use this weight vector $\mathbf{w}_{\mathrm{CR}}$, instead of separately applying the MRC weights on the samples obtained by the weight vectors $\mathbf{w}_{\mathrm{V},n}$.

4 Performance Evaluation

The simulations are carried out for the system setup explained in Sect. 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 1 × 4 SIMO configurations are used for both the primary signal and the CR signal.

The number of spatial channel realizations simulated in these experiments is 300. 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). A very basic training symbol scheme is assumed for the CR: training symbols contain pilots in all active subcarriers and the spacing of training symbols is 8 OFDM symbols. 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. We have tested the BS-CR link performance with SIR values of {−10, −20, −30} dB using silent gap durations of {8, 16, 32} OFDM symbols, and data block lengths of {17, 25, 33, 41} OFDM symbols.

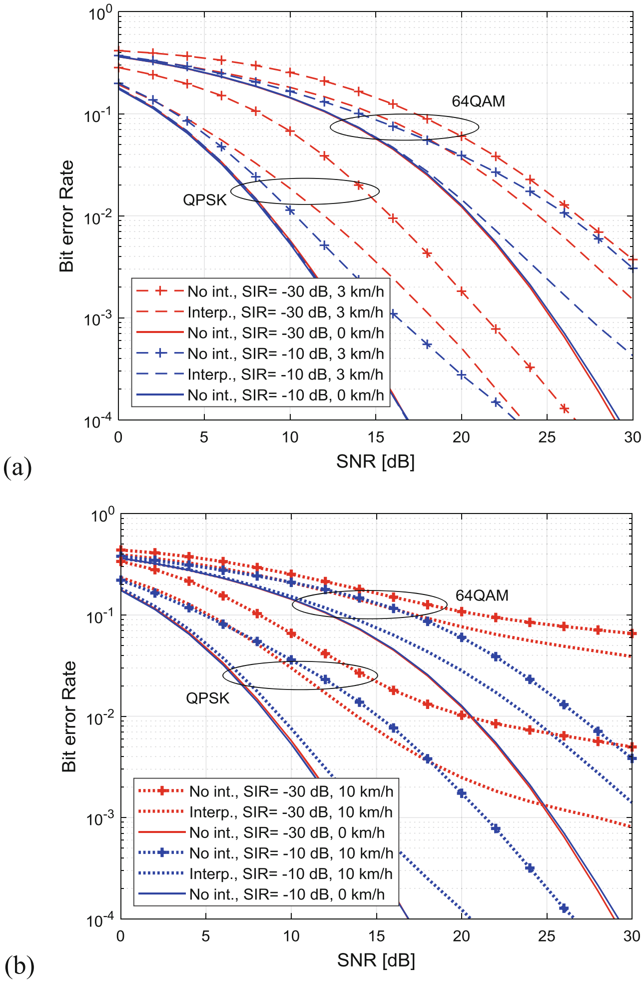

Fig. 2. Performance of QPSK and 64QAM BS-CR systems for SIR $\in \{-10, -30\}$ dB with or without covariance matrix interpolation. (a) 0 and 3 km/h CR receiver mobilities. (b) 0 and 10 km/h CR receiver mobilities. Silent gap length of 16 symbols, and OFDM frame length of 17 symbols.

Figure 2 shows the impact of covariance matrix interpolation on the BS-CR link performance. Here the data block length and gap duration are fixed to 17 and 16 OFDM symbols, respectively. This choice provides performance that is no more than 1 dB from the configuration reaching 1% or 10% BER with lowest SNR, among the tested configurations with even higher overhead. We can see that covariance interpolation provides significant improvement of robustness in time-varying channels. Focusing on the 1–10% BER region, the performance with interpolation at 10 km/h mobility clearly exceed the performance at 3 km/h without interpolation. However, for the 64QM case with −30 dB SIR, this is true only for BER of 10% or higher, due to the high error floor at very low SIR and high mobility. We can also see that with stationary channel, the performance is practically independent of the SIR (comparing with [9] the performance is slightly improved by fine-tuning the used algorithms).

In Fig. 3, the effect of silent gap duration is tested with 16 QAM modulation, SIR of −20 dB, and data block length of 17. The overhead in data rate is about 58% and 44% for gap lengths of 16 and 8, respectively. The shorter gap length results in about 1.5 dB performance loss in the 1–10% range in stationary case and about 1.8–3.5 dB loss with 10 km/h mobility, compared to the gap length of 16. With 20 km/h mobility, the corresponding loss is about 2.2 dB at 10% BER, but longer gap leads to higher error floor, and the performance with shorter gap becomes better for BER below 3%.

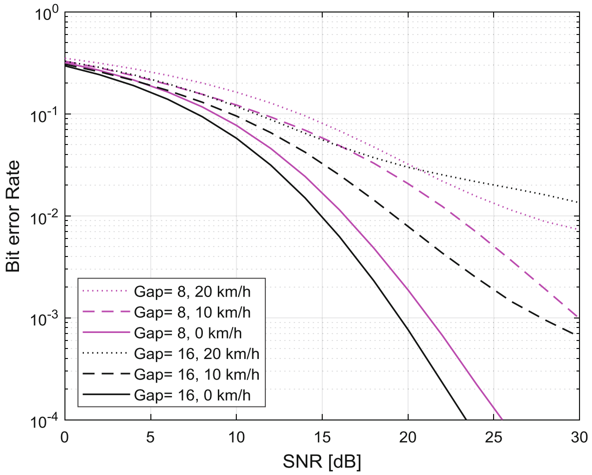

Fig. 3. Performance of QPSK and 16QAM BS-CR systems for SIR = −20 dB with covariance matrix interpolation for CR receiver mobilities of 0, 10 km/h, and 20 km/h. Silent gap length of 8 or 16 symbols and OFDM frame length of 17 symbols.

5 Conclusion

The performance of black-space CR transmission links in the presence of strong interferences and mobility was investigated using spatial covariance interpolation between silent gaps. The interference rejection capability of IRC using multiple receive antennas for various modulation orders under varying mobility and channel setups 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, e.g., due to people moving close to the CR receiver. 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 in the order of 16–32 OFDM symbols provides optimum performance with stationary channels, but even with 3 km/h mobility, the performance degrades greatly when considering SIR levels below −10 dB. The data block length should be of the same order or less, which leads to high overhead due to the silent gaps. Covariance interpolation was shown to greatly improve the robustness with time-varying channels, such that good link performance can be obtained with up to 20 km/h mobility at 700 MHz carrier frequency. This indicates that the proposed BS-CR scheme could be feasible at below 6 GHz frequencies with pedestrian mobilities. However, there is a significant tradeoff between link performance and overhead in data rate due to the silent gaps.

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 additional interference sources following the model of Eq. (1).

In future work, it is important to optimize the silent gap and data block lengths along with the modulation order to maximize throughput with given PU interference level and mobility. Lower-order modulations are more robust to errors in covariance estimation, allowing significantly lower gap and training overhead than higher order modulation. Complexity reduction of the covariance interpolation and IRC process is also an important topic for further studies. It is also 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 future studies, also the effect of antenna correlation will be taken into consideration.

Acknowledgment. This work was supported in part by the Finnish Cultural Foundation.

References

1. Yucek, T., Arslan, H.: A survey of spectrum sensing algorithms for cognitive radio applications. IEEE Commun. Surv. Tutor. **11**(1), 116–129 (2009)
2. Zeng, Y., Liang, Y.C., Hoang, A.T., et al.: A review on spectrum sensing for cognitiveradio: challenges and solutions. EURASIP J. Adv. Signal Process. **2010**, 381465 (2010). https://doi.org/10.1155/2010/381465
3. Dikmese, S., Srinivasan, S., Shaat, M., et al.: Spectrum sensing andresource allocation for multicarrier cognitive radio systems under interference and powerconstraints. EURASIP J. Adv. Signal Process. **2014**, 68 (2014). https://doi.org/10.1186/1687-6180-2014-68
4. Wyglinski, A.M., et al.: Cognitive Radio Communications and Networks: Principles and Practice. Academic Press, Cambridge (2010)

5. Selén, Y., Baldemair, R., Sachs, J.: A short feasibility study of a cognitive TV black space system. In: Proceedings of the IEEE PIMRC 2011, Toronto, ON, pp. 520–524 (2011)
6. Rico-Alvariño, A., Mosquera, C.: Overlay spectrum reuse in a broadcast network: covering the whole grayscale of spaces. In: Proceedings of the IEEE DySPAN 2012, WA, pp. 479–488 (2012)
7. Wei, Z., Feng, Z., Zhang, Q., Li, W.: Three regions for space-time spectrum sensing and access in cognitive radio networks. IEEE Trans. Veh. Technol. **64**(6), 2448–2462 (2015)
8. Beyene, Y., Ruttik, K., Jantti, R.: Effect of secondary transmission on primary pilot carriers in overlay cognitive radios. In: Proceedings of the CROWNCOM 2013, Washington, DC, pp. 111–116 (2013)
9. Srinivasan, S., Renfors, M.: Interference rejection combining for black-space cognitive radio communications. In: Moerman, I., Marquez-Barja, J., Shahid, A., Liu, W., Giannoulis, S., Jiao, X. (eds.) CROWNCOM 2018. LNICST, vol. 261, pp. 200–210. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-05490-8_19
10. Carleial, A.B.: A case where interference does not reduce capacity. IEEE Trans. Inf. Theory **21**, 569–570 (1975)
11. Devroye, N., Mitran, P., Tarokh, V.: Achievable rates in cognitive radio channels. IEEE Trans. Inf. Theory **52**, 1813–1827 (2006)
12. Verdu, S.: Multiuser Detection. Cambridge University Press, Cambridge (1998)
13. Winters, J.: Optimum combining in digital mobile radio with cochannel interference. IEEE Trans. Veh. Technol. **2**(4), 539–583 (1984)
14. Liaster, J., Reed, J.: Interference rejection in digital wireless communication. IEEE Signal Process. Mag. **14**(3), 37–62 (1997)
15. Klang, G.: On interference rejection in wireless multichannel systems. Ph.D. thesis, KTH, Stockholm, Sweden (2003)
16. Beach, M.A., et al.: Study into the application of interference cancellation techniques. Roke Manor Research Report 72/06/R/036/U, April 2006
17. Bakr, O., Johnson, M., Mudumbai, R., Ramchandran, K.: Multi antenna interference cancellation techniques for cognitive radio applications. In: Proceedings of the IEEE WCNC (2009)
18. Cheng, C.C., Sezginer, S., Sari, H., Su, Y.T.: Linear interference suppression with covariance mismatches in MIMO-OFDM systems. IEEE Trans. Wirel. Commun. **13**, 7086–7097 (2014)
19. Srinivasan, S., Dikmese, S., Menegazzo, D., Renfors, M.: Multi-antenna interference cancellation for black space cognitive radio communications. In: Proceedings of the 2015 IEEE Globecom Workshops, San Diego, CA, pp. 1–6 (2015)
20. Ladebusch, U., Liss, C.A.: Terrestrial DVB (DVB-T): a broadcast technology for stationary portable and mobile use. In: Proceedings of the IEEE, vol. 94, pp. 183–193, January 2006
21. Haykin, S.: Adaptive Filter Theory, 4th edn. Prentice-Hall, Upper Saddle River (2001)
22. He, C., Peng, Z., Zeng, Q., Zeng, Y.: A novel OFDM interpolation algorithm based on comb-type pilot. In: 5th International Conference on Wireless Communications Networking and Mobile Computing, WiCom 2009, pp. 1–4 (2009)
23. Cimini, L.J.: Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing. IEEE Trans. Commun. **33**(7), 665–675 (1985)