Silent Subcarrier Based Interference Rejection Combining for Mobile Black-Space Cognitive Radios

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Abstract. In this paper, we investigate the interdependence of sample covariance estimation structure and transceiver mobility in the black-space cognitive radio (BS-CR) context. Here the BS-CR utilizes multi-antenna interference rejection combing (IRC) schemes to enhance the reception. These BS-CR algorithms and schemes enable effective spectrum reuse of the primary user (PU) for CRs, especially over short-distance. The BS-CR and the PU system apply orthogonal frequency division multiplexing (OFDM) scheme using equal subcarrier spacing and equal cyclic prefix (CP) length. Then we can assume flat fading at the subcarrier level, which allows to use subcarrier-wise IRC processing. During silent time/frequency gaps in the CR transmission, the receiving CR station uses sample covariance matrix based IRC adaptation. We focus on comparing the performance between our new approach, silent subcarriers, against the earlier-used silent time-domain gap method in case of relatively low mobility. We present an experimental study of how the CR link performance varies depending on the structure of the silent gaps used for covariance estimation, the path delay profile of the propagation channel, and the velocity of the mobile CR. The performance evaluation is provided assuming 4G LTE-like signal structure for the PU.

Keywords: : Black-space cognitive radio, IRC, MRC, multiple antenna system, OFDM, sample covariance, silent subcarrier, underlay CR.

1 Introduction

The free wireless spectrum is sparse and valuable resource. Current and next generation wireless technologies rely on efficient use of it. Spectrum reuse is one of the well-known techniques by which efficient spectrum usage can be increased. Cognitive radios (CRs) play a prominent role in bringing such spectrum reuse to reality [1], [2]. One important challenge for the CR is that it is reliably operable in the presence of high levels of interference in its radio environment while, simultaneously, adding only ignorable interference to the primary users (PUs). Enabling mobility has been an important aspect of wireless communication systems which has ensured its success and relevance for many generations.

In wireless system design, additional attention has to be paid when there is user mobility. It adds to the complexity of the design and limits the system performance in perceivable manner, especially in transmission schemes which apply interference cancellation techniques. When spectrum efficiency and mobility are combined in a design, orthogonal frequency division multiplexing (OFDM) based transmission schemes become vital.

Our study focuses on the multi-antenna receiver diversity schemes which are used in the black-space cognitive radio (BS-CR) receiver. Specifically, we consider CR receivers with multiple antennas using spatial-domain interference rejection combining (IRC) to reduce the effects of co-channel interference. In this application, the CR transmission power is much lower than the power of the interfering PU which, on one hand, protects the PU transmission link from CR interference, but causes sever PU interference to the CR transmission, on the other. Here we mainly focus on the performance and interference rejection capability of such systems with mobility. The IRC receiver applies minimum mean squared error (MMSE) criterion for optimal multi-antenna co-channel interference cancellation [3]. The similarity of IRC and MMSE-based interference cancellation were discussed in [4]. Reference [5] discusses the use of antenna arrays in an adaptive manner for cancelling interference in the OFDM based systems. Also RF imperfections have perceivable impact on IRC receiver's performance [6], [7].

We consider BS-CR operation with a 4G LTE-like system as the PU, e.g., for device-to-device (D-to-D) communication underlaying LTE downlink transmission close to a base-station [8]. The IRC performance analysis is also relevant for cell-edge users' interference control utilizing IRC [9]. We focus on the scenario where a single active PU is transmitting continuously. The scenario can be extended to include multiple independent (uncoordinated) CR systems using the same OFDM numerology, in addition to the PU [8]. For the IRC schemes, the estimation of the spatial covariance matrix of the interfering signal(s) is essential. Sample covariance is used for this purpose, and it is estimated from the signal received by the CR station during silent time-/frequency-domain gaps in the CR communication signal. In particular, this paper's main contributions are:

- We refine the studies in [10]− [12] on IRC based BS-CR schemes considering now operation under CP-OFDM based LTE-like PU system with mobility and severe interference conditions.
- We investigate the use of silent subcarriers (SSCs) instead of silent time-domain gaps (STGs) for sample covariance estimation.
- The interference suppression quality and link performance of STG-based and SSC-based schemes are compared with different channel delay profiles, CR mobilities, and signal-to-interference ratios (SIRs), considering the overhead in throughput caused by the silent gaps.

The organisation of this paper is as follows: In Section 2, the elementary BS-CR scenario and general idea of the IRC scheme are explained. The IRC process and system modelling are explained in Section 3. Section 4 describes the setup used in our simulations and the results of the performance evaluation. Finally, concluding remarks are provided in Section 5.

2 Scenarios and Methods for IRC-based BS-CR

Fig. 1 shows the fundamental approach of IRC based BS-CR in which the data from a single antenna based CR transmitter is processed in a multi-antenna based CR receiver. The details of the scheme are given in the next section. In this scenario, CR and PU are supposed to work at the same carrier frequency and PU is much stronger than CR in terms of power spectral density (PSD) at the CR receiver. Additionally, it is considered that the PU is always active when there is a transmission by the CR. Then strong interference is created from PU to CR that works with low signal-to-noise ratio (SNR). Because of this, the transmission of the PU is secured. We focus on BS-CR systems with relatively short link-distances, like an indoors CR or cellular network underlay D-to-D communication [8]. Single-input multiple output (SIMO) antenna configuration is assumed for both PU and CR.

In our study, CP-OFDM waveform is considered for both PU and CR systems, using LTE numerology for both. The target is to have quasi-synchronous transmission where the received primary and secondary CP-OFDM symbols are overlapping with timing errors that are small compared to the CP length. Then it is essential to have common subcarrier spacing and common CP length, while the number of active subcarriers (as well as the IFFT length) of the CR can be smaller than that of the PU. Precise synchronization between PU and CR is assumed in both frequency and time domains. The CP duration should be enough to cover the channel delay spreads of PU and CR, together with the residual timing offset between PU and CR. Then it follows that the flat-fading circular convolution model applies at subcarrier-level for both the PU channel and the CR channel. Since there is no intercarrier interference, the IRC processing can be implemented separately for each subcarrier. Due to the high SNR of the PU signal, robust synchronization of the CR with the PU can be achieved without difficulties. Due to limited coverage of the CR systems, both the target and interfering CR links can be assumed to be short. This leads to short delay spreads for the CR channels, which has minor impact on the time alignment of the target CR and PU signals. In case of short-range CR systems, if all CR signals are synchronized with each other, they are also synchronized with the PU with small timing offsets. Quadrature amplitude modulation (QAM) is used for subcarriers, but the modulation alphabets can be different. It is also noted that PU and CR can use different frame and pilot structures.

In summary, the signal received at the CR station contains the target CR signal at low power level, the strong interfering co-channel PU signal, and in the generic case, also other interfering CR signals at low power level, all synchronized in quasi-synchronous manner.

2.1 Methods

Our scheme can be divided into three stages of CR receiver operation, as seen Fig. 1 [12]. First the spatial properties of the PU interference are modeled by the multi-antenna sample covariance matrix, estimated separately for each active

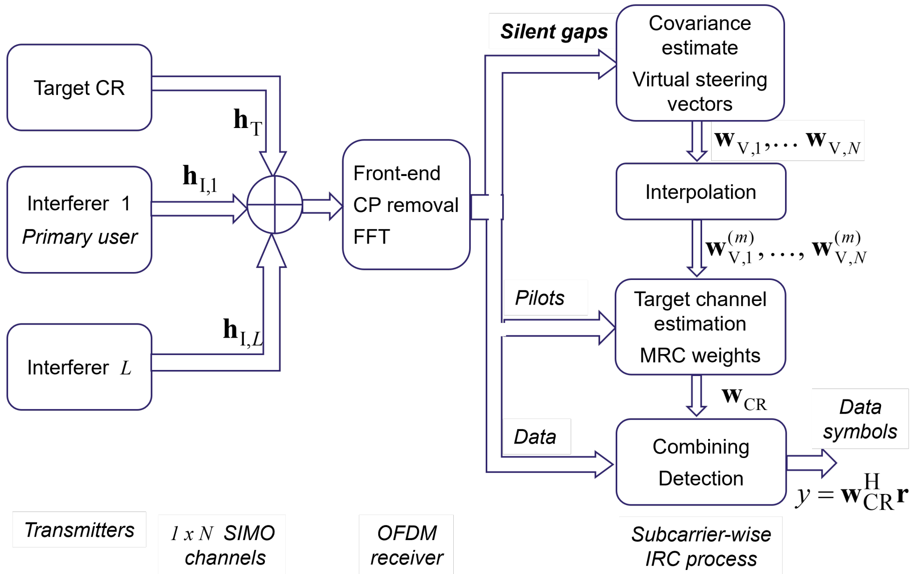


Fig. 1. Block diagram of black-space cognitive radio.

subcarrier. In the second step, the spatial CR channel is estimated using a number of co-channel interference -free signals obtained by IRC. In the third step, the optimal weight vectors are calculated for data symbols using interpolated covariance and channel estimates, and the data symbols are detected.

We investigate the impacts of channel fading with mobility when using the IRC scheme of Fig. 1. We compare sample covariance matrix interpolation based IRC schemes with interpolation in time direction or frequency direction with STG [12] and SSC models, respectively. The use of silent subcarriers with interpolation in frequency direction is a novel idea and it is expected to improve the tracking of fading channels with mobility.

3 IRC for Black-space Cognitive Radio

Having the same OFDM numerology for the PU and CR makes it possible to apply flat-fading channel coefficients for subcarrier-wise detection, in order to avoid the difficulties of frequency-selective IRC process. In the considered multi-antenna configuration, there are $L < N$ different interference sources and the CR has N receiving antennas. For an active subcarrier the signal can be expressed as (for simplicity, the subcarrier index is not shown):

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

Here, x_T is a transmitted sub-carrier symbol and $\mathbf{h}_\mathrm{T} = [h_{\mathrm{T},1}, h_{\mathrm{T},2}, \ldots, h_{\mathrm{T},N}]^\mathrm{T}$ is the target CR's channel vector, $x_{\mathrm{I},l}$ is the lth interfering symbol, and $\mathbf{h}_{\mathrm{I},l} = [h_{\mathrm{I},l,1}, h_{\mathrm{I},l,2}, \ldots, h_{\mathrm{I},l,N}]^\mathrm{T}$ is the channel vector for the lth interferer. The channel vectors consist of the complex channel gains from the corresponding transmit antenna to nth antenna of the CR. Finally, η is the additive white Gaussian noise (AWGN) vector. Generally, PU is assumed to be the dominant interferer while other co-channel CR's may introduce additional interference at low power level. In this paper, we focus is on the PU interference. The effect of interfering nearby BS-CR systems has been analyzed in [12].

3.1 Estimation of the spatial covariance matrix

The first step of the IRC process is interference covariance matrix estimation for each active subcarrier. A natural reference method in performance evaluation is the case where the channel of the PU is known and it is used for the spatial covariance estimation. Then the covariance matrix can be expressed as [7]

$$\boldsymbol{\Sigma}_\mathrm{NI} = P\mathbf{h}_\mathrm{I}\mathbf{h}_\mathrm{I}^\mathrm{H} + P_N\mathbf{I} \tag{2}$$

where P is the received PU signal power, P_N is the noise power, $\mathbf{I}$ is $N \times N$ identity matrix, and superscript H denotes the Hermitian (complex-conjugate transpose). During silent gaps, Eq. (1) is modified as:

$$\hat{\mathbf{r}} = \sum_{l=1}^{L} \mathbf{h}_{\mathrm{I},l} x_{I,l} + \boldsymbol{\eta}. \tag{3}$$

Then the covariance matrix estimate is:

$$\boldsymbol{\Sigma}_\mathrm{NI} = \frac{1}{M} \sum_{m=1}^{M} \hat{\mathbf{r}}\,(m)\,\hat{\mathbf{r}}(m)^\mathrm{H}, \tag{4}$$

where m is the OFDM symbol index and M is the observation length in OFDM symbols.

Due to the strong PU interference, it is difficult to obtain the target CR channel's impulse/frequency response. Therefore, we first obtain a set of IRC weight vectors which minimize the PU interference (in the generic case, also the low-power CR interferers) and use them for CR channel estimation during CR transmission. Based on these CR channel estimates, the actual weights for the CR signal detection are calculated [12].

In our earlier studies [10]– [12], we have used periodic time-domain silent gaps, in all subcarriers of the target CR transmission, between blocks of multiple OFDM data symbols. Now we evaluate the silent subcarrier model where the data subcarriers are active all the time, while selected subcarriers are silent all the time for sample covariance estimation. In this paper we assume that every second subcarrier is silent, while the effects of wider silent subcarrier spacing is a topic for further studies.

3.2 Interpolation-based interference covariance tracking with mobility

The mobilities of PU transmitter, CR receiver, and CR transmitter affect in different ways in the interference covariance estimation [6]. Even in the case where both PU and CR are stationary, the multipath transmission channel may vary if people or vehicles are moving close to the stations. Therefore, some tolerance to mobility is needed, at least with pedestrian velocities. While utilizing the sample covariance method, increasing the observation length M provides improved interference covariance estimate with zero/low mobility. However, variations of the PU-to-CR channel during silent gaps may greatly distort the interference covariance. Therefore, the optimum silent gap length depends on the mobility. The primary metric here is the Doppler spread, which is proportional to the used carrier frequency.

Interpolation of the channel response or covariance matrix elements during the data blocks between two consecutive STGs is a way to improve the interference covariance estimation quality. We have used linear interpolation of the covariance matrix between two STGs, which was found to greatly improve the CR link performance [11], [12]. Longer gap provides better performance with low mobility but reduces the performance with higher mobility and reduces spectrum efficiency. Longer data block improves spectrum efficiency but reduces the performance with mobility, since the distance between STGs is increased.

In silent subcarrier approach, a sliding sample covariance estimation process with chosen observation length can be applied. For each OFDM data symbol, the covariance estimate of selected length can be calculated from spatial interference samples that are symmetrically around the data symbol in time. This is expected to improve the tracking of the interference covariance variations. But now we have to interpolate the covariance estimate for the data symbols in frequency direction, from the covariance estimates obtained for nearby silent subcarriers.

3.3 IRC process

Our STG and SSC based IRC schemes are based on the block diagram of Fig. 1. For a given target channel vector $\mathbf{h}_{\mathrm{T}}$ (known as steering vector), the optimal interference-free signal can obtained using the linear combining weight vector

$$\mathbf{w} = \mathbf{\Sigma}_{\mathrm{NI}}^{-1}\mathbf{h}_{\mathrm{T}}. \tag{5}$$

But it is important to notice that interference-free signals are obtained with (almost) any steering vector. Our scheme provides first the weight vectors for N virtual steering vectors utilizing the STG or SSC based covariance estimate. Without loosing generality, N-element unit vectors are used as virtual steering vectors. Then N interference-free variants of the CR signal block are obtained using these weight vectors. Then we estimate the spatial channel of each variant utilizing the pilot symbols in these signals. Channel estimates for data symbols in each variant are obtained by interpolating between pilots. Finally, maximum ratio combining (MRC) is used for combining the N data symbol observations. Details of this approach can be found in [12] for the STG case.

It should be noted that, since L degrees of freedom are consumed by IRC, it could be enough to use $N-L$ vectors in this process. However, using N virtual steering vectors makes the process more straightforward, generic, and robust since estimation of the number of interferers can be avoided. In practical implementation, the optimal weight vectors for data symbols can be calculated directly from the interpolated interference covariance estimate $\mathbf{\Sigma}_{\mathrm{NI}}^{-1}$, virtual steering vectors (unit vectors) $\mathbf{h}_{\mathrm{V},n}$, and interpolated channel estimates $g_{\mathrm{V},n}$ as follows [12]:

$$\mathbf{w}_{\mathrm{CR}} = \sum_{n=1}^{N} \left(\mathbf{\Sigma}_{\mathrm{NI}}^{-1}\mathbf{h}_{\mathrm{V},n}\ g_{\mathrm{V},n}\right) / \sqrt{\sum_{n=1}^{N} |g_{\mathrm{V},n}\ \ |^2}. \tag{6}$$

The equalized data symbols are then obtained as follows:

$$\hat{d} = \mathbf{w}_{\mathrm{CR}}^{\mathrm{H}}\mathbf{r}. \tag{7}$$

This reduces the computational complexity, especially if the weight vector is interpolated between pilot symbols, instead of interpolating separately the channel estimates and the covariance matrix.

4 Simulation Results

CR link performance simulations are carried out with main OFDM parameters following the 4G LTE system, both for CR and PU: 15 kHz subcarrier spacing, FFT-size of 2048, 1200 active subcarriers, CP length of 144 samples, and 16-QAM as subcarrier modulation. The carrier frequency is 700 MHz and the Rayleigh-fading tapped delay line (TDL-C) channel model, commonly used in 5G-NR studies [13], is used as the fading multipath channel model. Different values of root mean square (RMS) delay spread parameter are considered: 50 ns as mildly frequency selective case, 250 ns as modest case, and 500 ns as strongly frequency selective channel. The corresponding maximum delay spread values are, $\{0.435, 2.175, 4.35\}$ μs, respectively, while the CP length is 4.7 μs. We consider all three choices for the PU but not including the strongly frequency selective case for the CR. In the figures, e.g., 'TDL-C 0.5/0.25' stands for strong/modest frequency selectivity for PU/CR, respectively. For PU and CR transmission links, independent instances of uncorrelated 1x4 SIMO antenna configurations are assumed. The CR pilot symbols are binary with the same energy as the data symbols. The CR pilots are located in every 7th OFDM symbol in all data subcarriers and the channel estimates for data symbols are obtained by linear interpolation, in time-direction in STG cases and in both time and frequency directions in SSC cases. In SSC cases, every second subcarrier is silent, i.e., the overhead due to silent parts for sample covariance estimation is 50 %. Similar overhead is considered also for the STG method when comparing the two schemes. 500 spatial channel realizations are simulated for the following

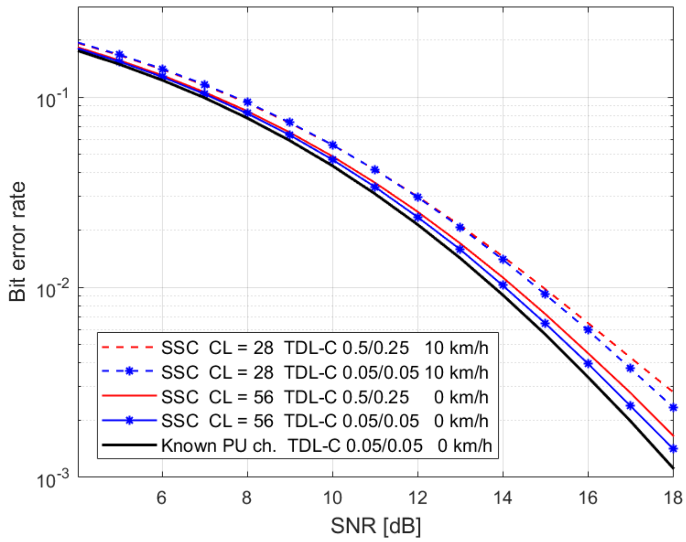
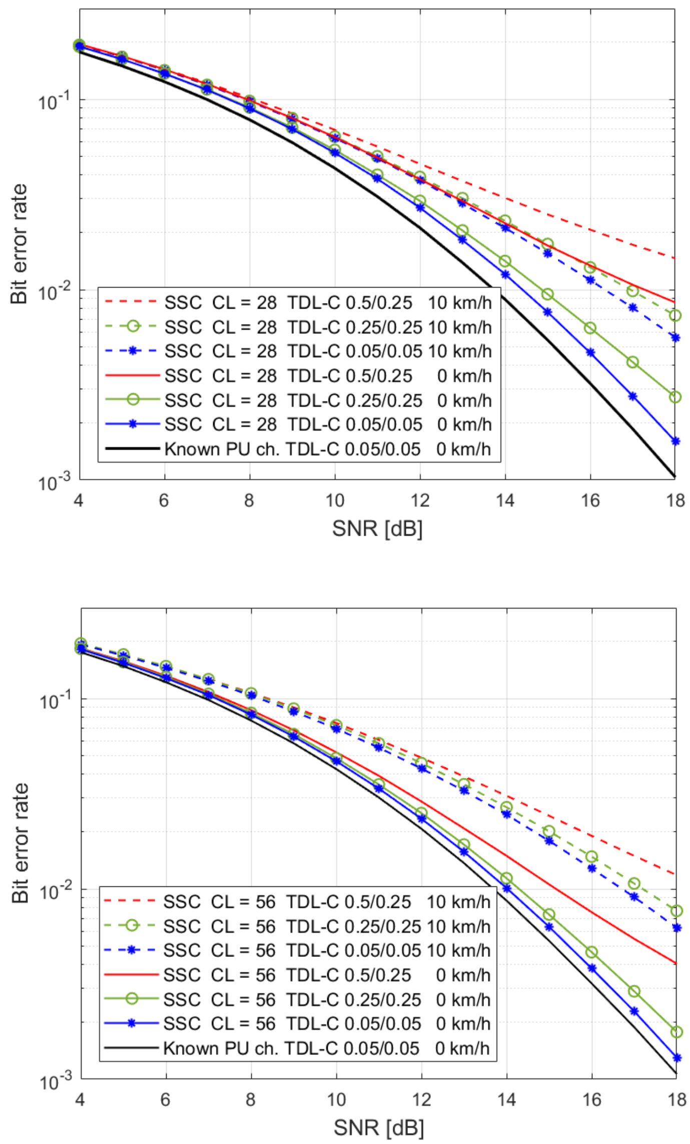


Fig. 2. Silent subcarrier based CR link performance in TDL-C channel with SIR = -10 dB, 0 and 10 km/h mobilities, and covariance lengths 28 and 56.

results. Here SIR is the ratio of CR and PU powers, and different SIR values are tested in the simulations. The OFDM symbol block length and, in STG cases, the silent gap length are varied and expressed in terms of CP-OFDM symbols. Data/pilot block length are such that training symbols appear in all active subcarriers as the first and last symbol of each block, along with possible other positions. The BS-CR link performance is tested with SIR values of {-10, -20} dB and covariance estimation lengths of {28, 42, 56}.

The simulation results include also the ideal reference case where the spatial covariance calculation is based on PU channel knowledge at the CR pilot locations. The covariance estimates are interpolated in time direction between CR pilots. Also here the CR channel estimation is based on the CR pilots, so the differences between known channel reference and simulated SSC and STG schemes are due to imperfect spatial covariance estimation.

Fig. 2 shows the bit error rate (BER) performance for the SSC method with SIR = -10 dB, zero and 10 km/h mobility in mildly frequency selective and strongly frequency selective PU channels using covariance estimation lengths of 28 and 56 OFDM symbols. With zero mobility, the SSC performance improves with increasing covariance length. However with given mobility, the performance starts to degrade after a certain covariance length. Withe the considered alternatives, 56 is the best choice with zero mobility and 28 with 10 km/h mobility. While the PU signal is 10 dB stronger than the CR, the effects of 10 km/h mobility and strong frequency selectivity of the PU channel are rather weak, about 1 dB SNR loss. With zero mobility, the loss is about 0.5 dB.



(a)

(b)

Fig. 3. Silent subcarrier based CR link performance in TDL-C channel with SIR = -20 dB, 0 and 10 km/h mobilities, and covariance lengths (a) 28, (b) 56.

Fig. 3 shows corresponding SSC results with SIR = -20 dB, now including also the case of modest PU channel frequency selectivity. Now the performance with strong frequency selectivity is clearly degraded, even with zero mobility,

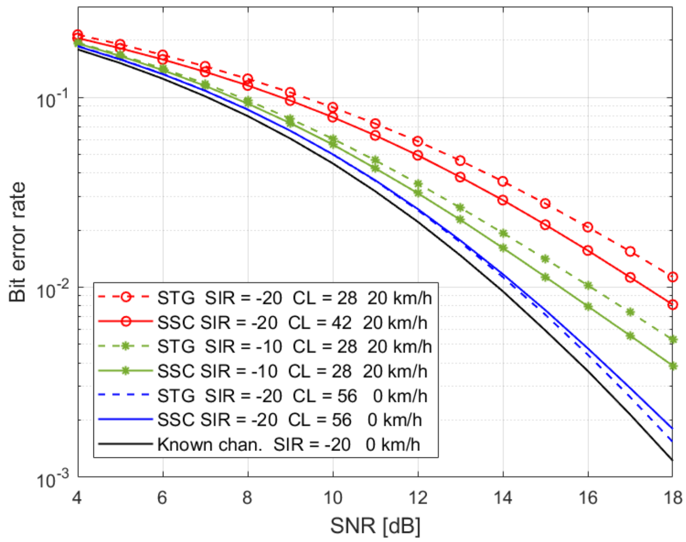


Fig. 4. CR link performance comparison of SSC vs. STG in TDL-C channel with modest PU and CR delay spread with SIR = {-10, -20} dB, 0 and 20 km/h mobilities, and optimum covariance lengths.

while the difference between small and modest frequency selectivity is relatively small. Longer covariance estimate clearly improves the performance with zero mobility, but covariance length of 28 is slightly better with 10 km/h mobility and small or modest PU channel frequency selectivity.

Finally, Fig. 4 shows the comparison between SSC and STG schemes with zero and 20 km/h mobility in TDL-C channel with modest (250 ns) RMS delay spread for both PU and CR. Optimum covariance length among {28, 42, 56} is used here for each case. In STG cases, the data block length is tuned to have the same (50 %) overhead due to silent parts as in the SSC cases. With zero mobility, the two schemes have quite similar performance, but with 20 km/h mobility, SSC scheme has about 1 dB SNR benefit over STG.

5 Conclusion

In this paper, we have elaborated silent subcarrier based sample covariance estimation for BS-CR. The scheme is generally available for IRC-based co-channel interference suppression. It has clear benefit over the earlier time-domain silent gap method with mobility. SSC scheme has also reduced latency and reduced need of signal buffering, since covariance estimate interpolation between silent gaps is an essential part of the STG scheme [11]. With strong interference level, both schemes have rather high overhead in throughput, even with limited mobility, which is unavoidable in sample covariance based approaches.

Generally, sample covariance based schemes allow straightforward blind spectrum reuse in complicated interference environments where PU channel estimation based schemes are not feasible. Notably, there is no need for the CR to have knowledge of the PU's pilot configuration. In further studies, it is also important to compare silent gap approaches with PU channel estimation based schemes considering limitations of the channel estimation process.

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