Low Access Latency and High Throughput for Full-Duplex Cognitive Radio Using Mobility Caching Placement Strategy

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Abstract

In a remote framework, the densely allotted radio range is not effectively utilized by an authorized primary user, which limits a secondary user to avoid disturbance to a primary user while utilizing a channel. To solve the shortage problem of accessible range, this study proposes a mobility caching placement strategy (MCPS) based sliding window scheme to optimize the latency and throughput of cognitive radio system. The performance parameters of the proposed system are analyzed using energy detection metrics by considering full-duplex communication. By the MATLAB analysis and the evaluation with and without self-interference suppression, the results demonstrate that the entrance inactivity of the MCPS based sliding window is diminished by a factor of 1.9 as contrasted with the existing full-duplex systems. With the improved latency and throughput, the proposed method can avoid the ruinous impacts of drawn-out self-residual suppression more effectively compared to the existing approaches.

Keywords: full-duplex cognitive radio, latency, mobility caching placement strategy, self-residual suppression

1. Introduction

One of the biggest difficulties in remote framework today is the shortage of accessible range, which can be resolved by using one of the best multiple access schemes, i.e., non-orthogonal multiple access (NOMA) [1]. Nonetheless, ongoing investigations have demonstrated that while the radio range is thickly allotted, it is frequently not intensely involved or utilized by an authorized primary user (PU) [2]. A recurrence coordinated cognitive radio (CR) system is proposed to exploit this circumstance while permitting an unlicensed secondary user (SU) to entrepreneurially reuse authorized recurrence groups without creating interference to the authorized user. One of the major necessities of such a framework is that SU ought not to produce destructive obstruction to PU [3-4]. Therefore, SU’s handset must be equipped for detecting the radio channel to decide whether PU is available or not by checking various performance parameters [5]. For range re-utilization, it requires low-inertness medium access for high-need users or high-need transmission. In this framework, a low latency-sensitive continuous transmission requires to be on hold for a split second as PU powerfully gets to the channel for getting its pressing message over. Such situations are of specific significance for the ongoing administration, for example, virtual/increased reality and independent vehicles. Therefore, it is required to get a latency of less than 1 msec to meet the forthcoming 5G systems [6].

Javed et al. [7] have given various methods to sense the PU spectrum with its pros and cons. Framework models that intermittently stop the SU transmission to detect the channel have been broadly proposed to recognize the beginning of the PU transmission and given various performance parameters’ comparison. These methodologies present visually impaired interims, where the SU framework is transmitting and becomes incapable of recognizing the beginning of the PU

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transmission. Diminishing the interim between progressive detecting spaces will decrease the proficiency and throughput of the SU framework; however, this will enhance its range detecting abilities. To solve this problem, Khalid et al. [8] and Singh et al. [9] described the use of a full-duplex scheme that senses the spectrum and transmits the data simultaneously, and Alves et al. [10] provides protection to the user's spectrum. Irio et al. [11] and Gaspard et al. [12] developed a method to expand the throughput of remote correspondence framework, where the remote terminal is permitted to transmit and sense at the same time in the same recurrence band. The throughput can also be increased by increasing the detection probability [13]. Tiwari et al. [14] proposed a cooperative medium access control (MAC) protocol called MLCP, which improves the throughput even more by enabling simultaneous transmission of PU and SU. Kumar et al. [15] proposed a clustering algorithm along with an energy efficient power allocation scheme due to which huge improvement in throughput is achieved. However, sustaining the improvement under imperfect self-interference cancellation is not addressed.

Mokhtarzadeh et al. [16] proposed a method to increase throughput for a full-duplex CR system. Previous research has analyzed the exchange of detection which requires further improvement to detect proficiency. The best way to enhance the identification of PU is by utilizing full-duplex CR under self-residual suppression (SRS), which senses the channel for every t_s test. This makes high access inertness as PU may begin the transmission whenever possible and can identify the nearness of PU more rapidly. Ayesha et al. [17] and Ayesha et al. [18] have described the alternative approaches of simultaneously sensing and transmission, using SRS for improving the trade-off between sensing the spectrum and SU throughput. However, the faultless SRS cannot be achieved below the noise floor.

In the existing work, the performance analysis of spectrum sensing is done by using various schemes and protocols, e.g., multi-objective modified grey wolf optimization algorithm [19], NOMA network under power splitting based simultaneous wireless information and power transfer (SWIPT) [20], NOMA based mobile edge computing with imperfect channel state information (CSI) [21], decode-and-forward (DF) and amplify-and-forward (AF) techniques in NOMA based cognitive radio network (CRN) [22], signal segmentation [23], neural network based multilayer perception model [24], and the channel allocation scheme based on greedy algorithm [25]. Cache technology is used to even improve the performance of parameters of spectrum sensing which includes various strategies: cache capacity allocation, cache replacement, cache utilization, and cache placement [26]. In the work of Zheng et al. [27] and Xia et al. [28], the performance improvement of parameters is analyzed including energy consumption optimization, system transmission performance, and latency.

In this study, a mobility caching placement strategy (MCPS) based sliding window scheme is proposed. This method significantly reduces access latency for the full-duplex system under SRS to protect PU. Additionally, it improves the SU throughput which maximizes the data transmission. This study emphasizes the issue of compromising the performance parameters of spectrum sensing (such as throughput and access latency) in the full-duplex CR under SRS. With different schemes, e.g., half-duplex, full-duplex using slotted window, and full-duplex using sliding window, the performance of parameters is evaluated with and without SRS. To optimize the sensing parameters, a MCPS based sliding window is proposed. Compared to the existing methods, the proposed method will exchange more information bits by taking decisions based on each sample, resulting in a quick detection of PU, in turn lowering the latency, and improving the SU throughput.

The study is organized as follows. The system model and frame structure of the existing methods and the proposed method is described in section 2. In section 3, the MCPS based sliding window scheme is discussed. The performance analysis of latency and throughput is analyzed in section 4. Analytical and simulation results are presented in section 5. Finally, section 6 concludes the study.

2. System Model

While SU is using the spectrum of PU, no interference in the PU network should occur. To ensure this, SU needs to accurately identify the white spaces for the transmission and should vacate and opt for the subsequent band when PU appears. The first scenario is considered hypothesis H_1. When PU is using the spectrum, the signal received at SU is expressed in Eq. (1). The second scenario is considered hypothesis H_0. While PU is not using the spectrum, the received signal can be expressed in Eq. (2).

$$S(n) = X(n) + u(n) \tag{1}$$

$$S(n) = u(n) \tag{2}$$

In the above equation, $X(n)$ is the signal which needs to be identified, $u(n)$ is the Gaussian noise which is additive white in nature, and n is the sample index. The parameters of performance using detection algorithm will be analyzed based on two probabilities: the detection probability (P_d) with hypothesis H_1 for identifying the presence of licensed user activity and the false alarm probability (P_f) with hypothesis H_0 for detecting the licensed user when the licensed user is actually not present. PU is effectively protected when the probability of detection is high. In another scenario, SU can use the frequency band recurrently when the false alarm probability is low and is available. To guarantee better performance of the system, the detection probability shall be as much as possible, and the false alarm probability shall be as minimum as possible.

CR system schemes are half-duplex and full-duplex, which are addressed in this section. The presence of detection of PU is done by using a metric M, which is compared with a given threshold γ for both schemes. PU is present if $M > \gamma$, otherwise PU is absent and SU can use the channel. Energy detection is the frequently used metric for sensing the spectrum [29].

$$M = \frac{1}{N_s} \sum_{n=1}^{N_s} \left| S(n) \right|^2 \tag{3}$$

where $S(n)$ is the SU received signal. If the PU information is known prior, other detection methods can be used. Using decision metric, the detection probability P_d and the false alarm probability P_f can be evaluated with the help of a hypothesis test [7].

$$P_f = P_r\left(M > \gamma / H_0\right) \tag{4}$$

$$P_d = P_r\left(M < \gamma / H_1\right) \tag{5}$$

The CR system frame structure is shown in Fig. 1. Initially, the CR system has to sense the spectrum and determine the status of PU. If the frequency band of PU is detected as idle, then the SU transmitter will make use of the band to transmit information to the SU receiver for the frame duration. If PU starts transmission, then SU has to cease its transmission, to avoid interference to PU. Again, in the next frame, SU will access the frequency band and the process repeats.

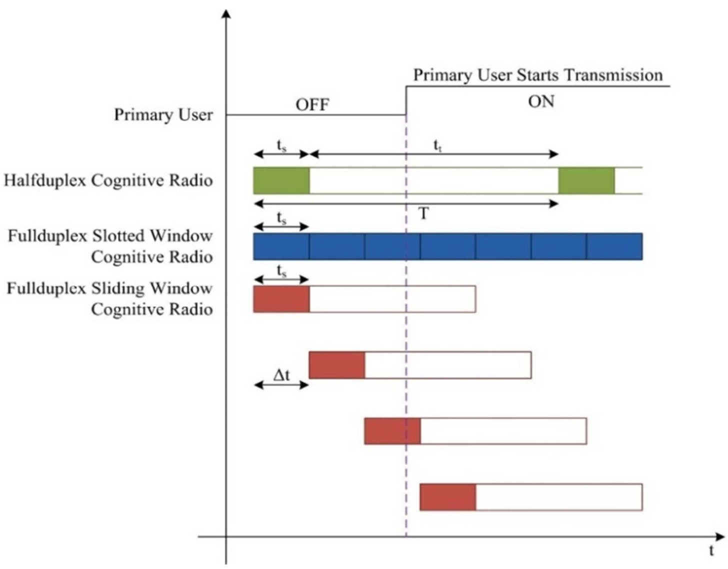

Fig. 1 Frame structure of CR system under SRS

2.1. Half-duplex CR system

In this scheme, spectrum sensing has to be scheduled sequentially with transmission, as shown in Fig. 2. The frame contains two parts: $T - t_t$ sample window for transmission and t_s sample window for sensing the frequency band. t_s samples are used to know the status of PU using Eq. (1) and thus decisions will be made for every T sample. It is clear that under the half-duplex scheme, SU has to cease the transmission each time the spectrum sensing is established, which leads to the higher access latency of PU and the reduction of SU throughput by a factor of $\frac{T-t_s}{T}$.

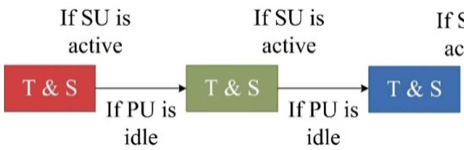

Fig. 2 Frame structure of half-duplex CR system

2.2. Simultaneous detection and transmission with slotted window scheme

The frame structure of simultaneous detection and transmission with a slotted window using SRS is shown in Fig. 3 [16]. It contains a single frame, in which both the sensing and transmission will be performed simultaneously to lead to the improvement in detection probability and the decisions made for every t_s. In this scheme, as there is no separate sensing slot, the SU throughput will not reduce, and SU can detect the status of PU immediately which leads to a reduction of latency.

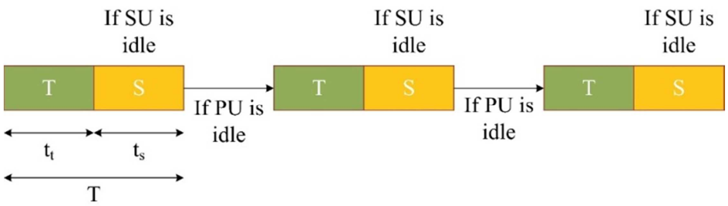

Fig. 3 Frame structure of slotted window full-duplex CR system

2.3. Sliding window scheme for simultaneous detection and transmission

The frame structure of simultaneous detection and transmission with a sliding window using SRS is shown in Fig. 4, where the decisions will be made for every sample compared to the slotted window (for every t_s). This scheme can be actualized effortlessly in computerized equipment employing a first-in first-out (FIFO) cushion. It is imperative to take a note that progressive choice measurements are not free as just a single new sample is included (and one is expelled).

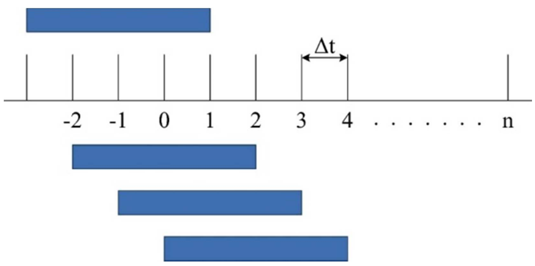

Fig. 4 Frame structure of sliding window full-duplex CR system

2.4. Quadrature phase shift keying

The major advantages of digital modulation techniques are the improved capacity to transmit huge data with high immunity and the easy detection of its distinct transmission state at the receiver in a noisy medium. While converting analogue signals to digital signals, a trade-off is always made due to the loss of some information in the quantization process. Proper selection of the digital modulation technique is crucial especially when the bandwidth and time slots are limited in uplink-downlink transmission. The efficacy of a modulation technique is restrained in terms of its bandwidth and power efficiency. The capability of a modulation technique in accommodating data within a limited bandwidth is regarded as bandwidth efficiency whereas the ability to preserve the bit error probability of the digital message at low power levels is treated as the power efficiency of a modulation technique.

With regards to the digital modulation schemes, for the same number of bits transmitted and received, binary phase shift keying (BPSK) modulation has less bit error rate and bandwidth for different values of signal-to-noise ratio (SNR), as compared to binary amplitude shift keying (BASK) and binary frequency shift keying (BFSK) modulation. To detect the message at the output, minimum SNR and low bit error rate with higher performance is required. With low power consumption, BPSK modulation technique provides the best performance even for less SNR.

Bandwidth can be saved even more in M-ary phase shift keying (M-PSK) modulation schemes by maintaining symbol rate constantly and increasing the number of bits per symbol. For example, in quadrature phase shift keying (QPSK), one of the 4 possible phase shifts per symbol can be transmitted rather than transmitting only 2 possible phase shifts so that 2 bits per symbol (i.e., for the same bandwidth with twice the information) can be transmitted [30]. Also, with the same energy efficiency, one can achieve double spectral efficiency.

Higher compound M-PSK modulation schemes can also be possible (8-PSK, 32- PSK, 64- PSK, etc.) to transmit more bits per symbol and in turn achieve higher bit rate. However, this employs higher vulnerability to noise as the symbols together get the closer and increased bit errors. In order to make a trade-off between bit rate and probability of error, QPSK is opted in the proposed system.

3. MCPS Based Sliding Window Scheme

Caching techniques are attracted expressively since they can decrease backhaul traffic and also improve performance metrics. Caching placement strategies can be of uncoded or coded type. Both are used for optimizing the performance of parameters. The MCPS scheme allows decisions to be taken on a multiple sample transfer at a time and increases the concurrent transmission and sensing using intra interference suppression, which checks the presence of PU continuously in a spectrum band and gives a perfect position. The operation of MCPS is shown in Fig. 5 and the flowchart is shown in Fig. 6. The number of input samples and coding rate is calculated by considering SNR, number of symbols present at the transmitter, and threshold value using Eqs. (6) and (7).

$$N = \frac{1}{2}\left(\sqrt{R_x} \times SNR\right) \times N_{bs} + ... + SNR\left(N_{bs}\right) \tag{6}$$

$$R_i = H \times (Thr + 10^{SNR/N_{tx}}) \times N \tag{7}$$

where N represents the number of samples, H is the analysis of H equation, SNR represents the signal-to-noise ratio, R_x is the receiver, Thr represents the threshold value, R_i represents the coding rate, and N_{tx} represents the number of symbols at the transmitter. A signal is passed through the QPSK modulator, then the modulated data is analyzed, processed using Eqs. (8)-(10), and then transmitted through the channel.

$$ipQ = \frac{1}{\sqrt{\phi(k)}} \times R_i - w(L) \times N_{bs} \times \phi(k) \times w(L) - N_{bs} \times R_i \tag{8}$$

$$ipQ = \frac{w(L)}{r_{tx}} \times w(L) \times N_{bs} \tag{9}$$

$$ipQ = w(s)\sqrt{w(L)} \times ifft \tag{10}$$

where $\phi(k)$ represents the phase of the signal, $w(L)$ is the line width, ipQ represents the quadrature input, r_{tx} represents the random information at transmitter, and $w(s)$ is the sample width. Parameter optimization is done by using Eqs. (11)-(17).

$$QP_T = NP_s \times c\left|R_i \times \frac{w(L)}{2}\right| \times (N_{bs} - N_{tx})\, j \times w(L) \times r_{tx} \times |w(L) \times N_{bs}| \tag{11}$$

$$QP_{T(R)} = \frac{w(s)}{\sqrt{w(L)}} \times ifft(QP_T \times R_i) \tag{12}$$

$$M_{SQP} = \sum\left[QP_T \times conj(QP_T)\right] \times \frac{r_{tx}}{w(s)} \tag{13}$$

$$P_v Q_p = Max\left[QP_{T(R)} \times conj\left(QP_{T(R)}\right)\right] - r_{tx} \tag{14}$$

$$M_{SRN} = \sum\left(QP_{T(R)}\right) \times conj(QP_T) - \frac{r_{tx}}{w(s)} \tag{15}$$

$$Gain = \frac{M_{SRN}}{M_{SQP}} \tag{16}$$

$$MSE = 10 \times \log_{10}(Gain) \tag{17}$$

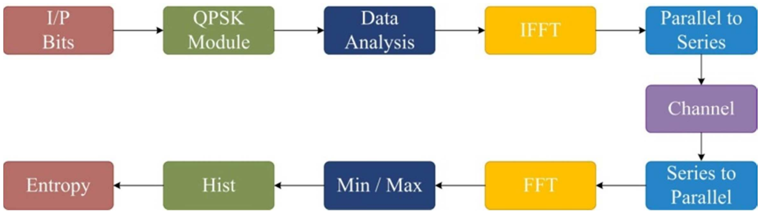

Fig. 5 Operation of MCPS

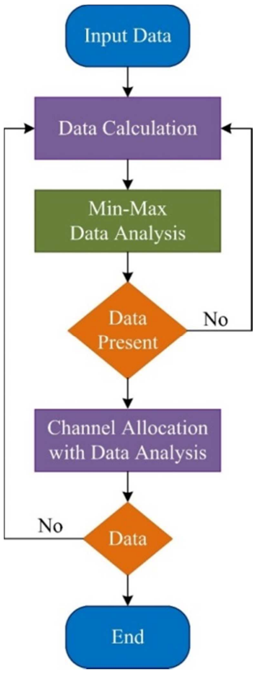

Fig. 6 Flowchart of MCPS

4. Performance Analysis

4.1. Analysis of latency and throughput in MCPS based sliding window

The impact of detecting time on the throughput is examined in this section. In each edge of the frame structure span T_F, SU starts sensing the channel for a period of sensing time (t_s), and if the channel is free (which indicates PU is not using the channel), then SU utilizes the channel (spectrum) for information transmission. On the other hand, if PU wants to use the channel, then SU has to evacuate the channel and use another channel that is free for transmission without creating interference to PU. If the length of the corresponding edge of PU is T_{PRF}, then the throughput of SU that could be transmitted when PU is not utilizing the spectrum is $T_{PRF} + T_F$. The throughput (Th) of SU is given by:

$$Th = \frac{T_F - t_s}{T_F}\left(1 - P_f\right)P_c \tag{18}$$

At the point, when PU has an exponential on-off movement display, with the mean spans of "on" period signified by β, then P_c is given by:

$$P_c = \exp\left(-\frac{T_{PRF} + T_F}{\beta}\right) \tag{19}$$

Expecting that the casing of span T_{PRF}, T_F, and false caution likelihood has been settled, then the standardized throughput of SU is:

$$Th = \frac{T_F - t_s}{T_F}\left(1 - P_f\right)\exp\left(-\frac{T_{PRF} + T_F}{\beta}\right) \tag{20}$$

For the case of H_0 (i.e., PU is available but wrongly detected), the probability density function (PDF) of the SU received signal (S) is $P_0(x)$, and the probability of false alarms P_f is:

$$P_f = P\left(S > \varepsilon / H_0\right) = \int_{\varepsilon}^{\infty} P_0\left(x\right)dx \tag{21}$$

The detection threshold $\mathcal{E}$ is calculated as:

$$\varepsilon = \sigma_u^{\ 2}\left[Q^{-1}\left(P_f\right)\sqrt{\tau f_s + 1}\right] \tag{22}$$

On the other hand, when PU is using the channel (for the case of H_1), the pdf of the SU received signal (S) is $P_1(x)$, and the detection probability P_d is:

$$P_d = \left(S > \varepsilon / H_1\right) = \int_{\varepsilon}^{\infty} P_1\left(x\right)dx \tag{23}$$

The latency (L) of the system is calculated as:

$$L = N_1 P(D_1) + N_2 P\left(\frac{D_2}{D_1^{\ c}}\right) + N_3 P\left(\frac{D_3}{D_1^{\ c} \cap D_2^{\ c}}\right) + ... + N_i P\left(\frac{D_i}{D_1^{\ c} \cap D_2^{\ c} ... \cap D_{i-1}^{\ c}}\right) \tag{24}$$

where N_i is the number of samples when PU begins with i^{th} decision point, D_i denotes the event when PU is detected at i^{th} decision once transmission starts, and D_i^c represents the complementary event when PU is not detected during i^{th} decision.

4.2. Algorithm

The algorithm of MCPS based on latency and throughput optimization is described in Table 1, where the input parameters need to be specified first and then the Eqs. (8)-(10) are analyzed. Furthermore, the optimization of latency and throughput are calculated based on the analytical values.

Table 1 Algorithm of MCPS

Input: N_s, N_{TX}, N_{RX}, CL, CW, bps, nsy
Output: Return the estimated data in the QPSK domain [var]
Begin
For i = 1 to $esN_0\ dB\ do$
j = 1 to $esN_0\ dB\ do$
$Z(h_k^i, n) = N_c(fs, ms, CW, CL)$
For k = 1………… $esN_0\ dB$ using 8-10 in var SW
Parameter Optimization
Learn (Latency Variance) Δ_n^t
Update (var name) η_n^t using
$t \rightarrow (t+1)$ or $(t-1)$
Throughput = $\sum \frac{(output-input)}{MSE}$
$MSE = log_{10} \sum \sum input[R_x c]$
End

5. Analytical and Simulation Results

This section explains the analytical and simulation results of the proposed MCPS technique under perfect SRS and imperfect SRS, as compared with the existing methods. Simulation results show the improvement in performance parameters by using the proposed technique. Simulation parameters of the MCPS scheme are shown in Table 2.

Table 2 Simulation parameters

Parameter	Value
Channel length	128
Number of bits	10^5
Number of sub-carriers	128
Number of transmitters	2
Number of receivers	2
Fast Fourier transform size	64
Sensing window size	16

5.1. Perfect self-interference suppression

Fig. 7 depicts the substantial improvement of latency and throughput with the MCPS based sliding full-duplex method compared to the existing methods under perfect SRS. Since half-duplex allows either sensing or transmission at a time and cannot perform both tasks at a time, the latency of this method is almost half of a SU frame length and throughput is also very less. Unlike half-duplex, the slotted full-duplex method allows both sensing and transmission at a time, and the latency of this method has been improved for a duration of $t_s/2$ compared to half-duplex since, for each t_s duration, there is a provision of taking decisions. As the decisions are taken for every sample, the sliding full-duplex method can detect the usage of the channel by PU quickly. Furthermore, compared to the sliding full-duplex, the latency of MCPS is improved by a factor of 0.98; compared to the slotted full-duplex, the MCPS latency is improved by a factor of 3.7; compared to half-duplex, the MCPS latency is improved by a factor of 20. Fig. 8 illustrates the different quantiles of optimization parameter trade-off for the proposed MCPS technique and the existing sliding and slotted techniques. The performance of parameters depends on self-residual, noise, and signal realizations. The results show the improvement of the proposed technique compared to the existing techniques.

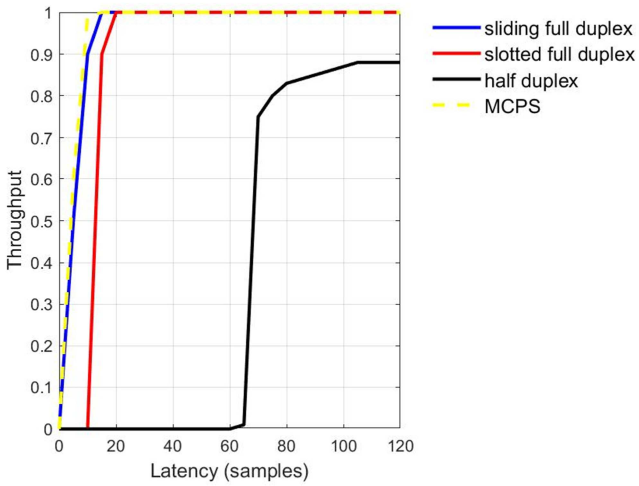

Fig. 7 Latency versus throughput comparison for all the 4 methods under perfect SRS

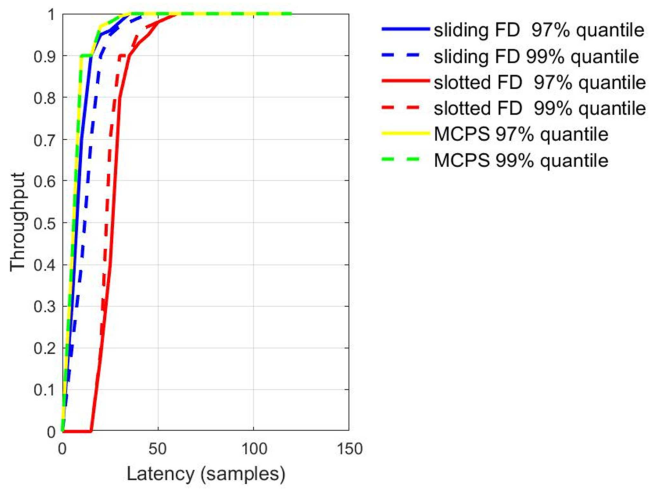

Fig. 8 Quantiles of optimization parameter trade-off under perfect SRS

5.2. *Imperfect self-interference suppression*

Fig. 9 depicts latency improvement for MCPS with an increase in SRS, measured with respect to the noise floor which is calculated by considering throughput to 0.9. When compared with the existing methods, the slotted full-duplex method has higher latency for all values of self-interference, but the proposed method can withstand the improvement of self-interference by a 3.2 factor. Fig. 10 depicts the throughput improvement for MCPS with increasing SRS. The MCPS method has improved the throughput under the PU protection. Table 3 shows the comparison of the parameters of the sliding full-duplex and MCPS methods.

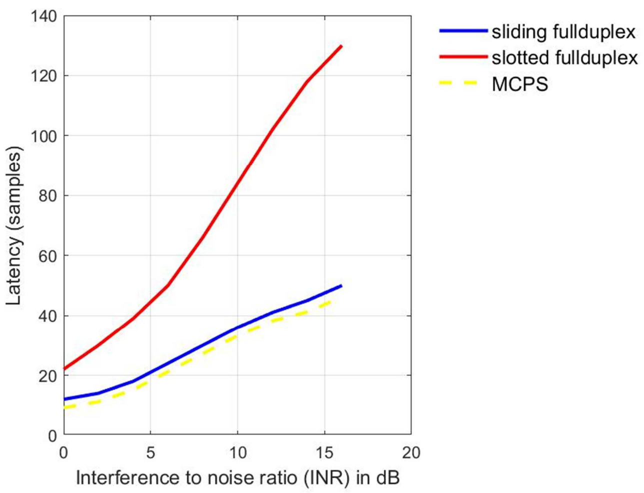

Fig. 9 Latency versus SRS

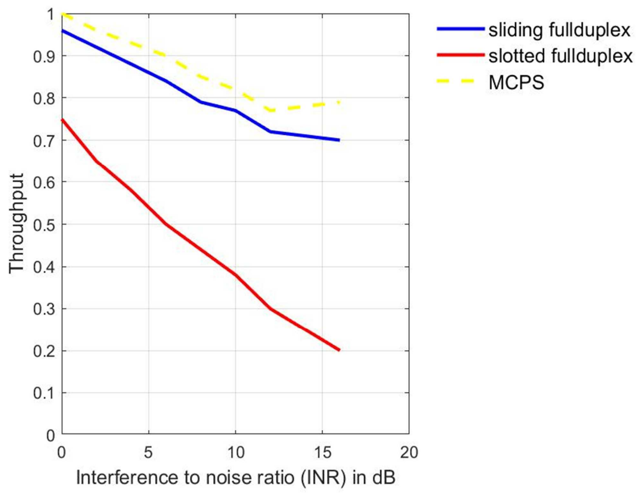

Fig. 10 Throughput with increasing SRS for the latency of 16 samples

Table 3 Comparison of parameters

Parameters	Sliding window full-duplex	MCPS
No. of transmitters (T_x)	2	2
No. of receivers (R_x)	2	2
Channel length	64	Up to 128
Number of bits	10^4	10^5
Channel size	52	52
Max latency	0.90	0.79
Throughput	0.78	0.89
Error rate	0.44	0.42
SNR	0.97	0.99

6. Conclusions and Future Scope

This study investigated CR from the point of view of ensuring the essential and high priority users under perfect SRS and imperfect SRS by diminishing the latency of the framework. By inferring systematic recipes for latency and throughput of the existing methods, the proposed method is beneficial in terms of its capacity to make choices at each sample. Additionally, the results of simulation show that the proposed sensing framework can achieve a huge improvement in latency and throughput under SRS, which is diminished by a factor of 1.9 contrasted with the current full-duplex system.

The performance parameters can be further extended by using vehicular ad-hoc networks, which provide cooperation in CR and share the channel status while switching between the channels when PU exists. Furthermore, the parameters can be extended by using a testbed that tests the performance and practicability of CR framework.

List of Acronyms

NOMA	Non-orthogonal multiple access	SNR	Signal-to-noise ratio
PU	Primary user	BASK	Binary amplitude shift keying
SU	Secondary user	BFSK	Binary frequency shift keying
CR	Cognitive radio	M-PSK	M-ary phase shift keying
MAC	Medium access control	R_x	Receiver
SRS	Self-residual suppression	N_{tx}	Number of symbols at transmitter
SWIPT	Simultaneous wireless information and power transfer	QPSK	Quadrature phase shift keying
CSI	Channel state information	$\phi(k)$	The phase of the signal
DF	Decode-and-forward	$w(L)$	Line width
AF	Amplify-and-forward	ipQ	Quadrature input
CRN	Cognitive radio network	r_{tx}	Random information at transmitter
MCPS	Mobility caching placement strategy	$w(s)$	Sample width
P_d	Probability of detection	MSE	Mean square error
P_f	Probability of false alarm	T_F	Frame structure span
FIFO	First-in first-out	$\mathcal{E}$	Detection threshold
BPSK	Binary phase shift keying	Th	Throughput of SU
t_s	Sensing time	B	Mean span of “on” period
t_t	Transmission time	T_{PRF}	Length of the corresponding edge of PU
$X(n)$	Detected signal	PDF	Probability density function
$u(n)$	Additive white Gaussian noise	L	Latency
M	Decision metric	N_i	Number of samples at i^{th} decision point
γ	Threshold	D_i	Event when PU detected at i^{th} decision
$S(n)$	Received signal	D_i^c	Complimentary event when PU is not detected during i^{th} decision
N	Number of input samples		

Conflicts of Interest

The authors declare no conflict of interest.

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