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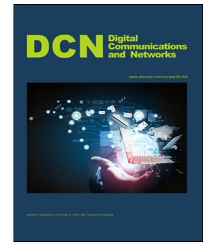

Wireless distributed computing for cyclostationary feature detection

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Abstract
Recently, wireless distributed computing (WDC) concept has emerged promising manifolds improvements to current wireless technologies. Despite the various expected benefits of this concept, significant drawbacks were addressed in the open literature. One of WDC key challenges is the impact of wireless channel quality on the load of distributed computations. Therefore, this research investigates the wireless channel impact on WDC performance when the latter is applied to spectrum sensing in cognitive radio (CR) technology. However, a trade-off is found between accuracy and computational complexity in spectrum sensing approaches. Increasing these approaches accuracy is accompanied by an increase in computational complexity. This results in greater power consumption and processing time. A novel WDC scheme for cyclostationary feature detection spectrum sensing approach is proposed in this paper and thoroughly investigated. The benefits of the proposed scheme are firstly presented. Then, the impact of the wireless channel of the proposed scheme is addressed considering two scenarios. In the first scenario, workload matrices are distributed over the wireless channel. Then, a fusion center combines these matrices in order to make a decision. Meanwhile, in the

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second scenario, local decisions are made by CRs, then, only a binary flag is sent to the fusion center.

1. Introduction

In the future wireless technology standard, local computing, where a single node performs all workload computations, is expected to face challenges in satisfying the required quality of service (QoS) levels such as power consumption or latency. Furthermore, the required high speed for computations, arrives at the saturation point of CPUs. In addition to the ability of new communication devices to collect and analyze data are the main reasons to turn to distributed computing [1-4].

According to [4], *"Distributed computing studies the models architectures and algorithms used for building and managing distributed systems."* Distributed system can be defined as the system where cooperating nodes communicate and coordinate their actions by passing messages [5]. The medium to communicate or coordinate actions is either wired or wireless links. Many research works in the open literature have explored wired distributed computing. However, wireless distributed computing (WDC) is a new concept that still faces enormous challenges. These WDC challenges are discussed in [3] and categorized mainly into three groups. Firstly, communication subsystem design which considers the challenge of channel robustness. This uncertainty of the wireless channel leads to a high bit error rate and random delay [6]. Thus, efficient methods to gather, relay or broadcast and buffer the distributed tasks between the cooperating nodes maybe required to overcome data loss and delay. Secondly, WDC networks are expected to face synchronization challenge. Synchronization is essential for heterogeneous applications in order to synchronize processing and communication operations between the cooperating cognitive radios (CR). Thirdly, network control challenges such as leaders election, topology control, i.e. the selection of the processing nodes based on the link quality, and workload allocation or tasks allocation that ensures efficient distribution of tasks among cooperating nodes.

Herein, the concept of WDC is employed to overcome the increasing computational complexity of an accurate spectrum sensing approach. Moreover, this research is motivated to investigate WDC with spectrum sensing due to the various benefits of WDC. This includes energy savings by reducing the consumed processing power per cooperating CR as well as distributing the workload efficiently to fit the requirements of the cooperating CRs by segmenting the main task to subtasks and allocating the tasks onto the best suitable processor. Furthermore, WDC reduces the processing time per cooperating CR and enable computing complex tasks that cannot be completed by local computing.

Amongst the common spectrum sensing approaches, i.e. matched filtering, cyclostationary feature detector and energy detection, WDC concept is applied to cyclostationary feature detector due to it's high level of accuracy but at the cost of computational complexity as well as it has been recommended by IEEE 802.22 standard [7]. WDC, however, is not a benefit in case of the energy detector spectrum sensing technique due to it's design simplicity and low computational complexity. In addition, WDC cannot be applied to match filtering spectrum sensing approach due to the demand for perfect knowledge of PU signals [8]. New research work for cyclostationary feature detector claimed that it is possible to detect the PU's signal without the relevant information of the signal attributes [9]. Another research has proposed detection and classification method for cyclostationarity detector without any prior knowledge of the transmitting signal except rough information on signal bandwidth [10]. Moreover, in order to facilitate obtaining the information to detect and analyze the signal cyclostationarity, signatures might be intentionally embedded in the PU signal as proposed in [11,12].

To the best of our knowledge, the first research that investigated applying WDC within spectrum sensing is [13] where the mathematical viability of applying WDC with strip spectral correlation algorithm (SSCA) is presented. In addition, the channel impact is highlighted using only one scenario where the workload of SSCA is distributed wirelessly between processing CRs.

The contributions of this research are:

a. Extension of the novel mathematical model to verify the viability of applying WDC with FFT time smoothing algorithms, i.e. FFT accumulation method (FAM) and SSCA.
b. Highlights the benefits of applying WDC with FFT time smoothing algorithms.
c. Investigates the channel impact on the proposed WDC with FFT time smoothing algorithms in case of transmitting workload matrices through the wireless channel. Even though, in the first scenario, the channel effect is highlighted in [13], it did not propose any solutions to reduce the channel degradation. Herein, the channel limitation is reduced by utilizing more realistic wireless links employing channel encoders.
d. Proposes novel scheme which transmits a binary flag instead of payload matrices.
e. Evaluates the performance of the proposed novel schemes by computing probability of detection P_D, probability of error P_E and ROC.

The rest of this research paper is organized as follows. Section 2 presents the proposed scheme of WDC with FFT time smoothing algorithms. Then, Section 3 justifies the proposed scheme mathematically. Later, Section 4 tests the performance of the proposed schemes against the conventional algorithms. Finally, the conclusion and recommendations for future work are drawn in Section 5.

2. The proposed scheme of WDC with cyclostationary feature detection

FFT time smoothing algorithms are the most efficient approaches to estimate the signal cyclostationarity [14]. Therefore, this section utilizes these algorithms with the proposed scheme. However, the computational complexity of FFT time smoothing algorithms is high. Therefore, this section begins with introducing FFT time smoothing algorithms and formulating the problem of their high level of computational complexity. Later, the proposed scheme of WDC with FFT time smoothing algorithms is explained.

2.1. FFT time smoothing algorithms

Dandawate and Giannakis [15] presented two statistical tests to detect signals cyclostationarity. The first is a time domain test which detects the signal cyclostationarity by evaluating the cyclic autocorrelation function (CAF) while the second is a frequency domain test that estimates the cyclostationarity by computing the spectral correlation function (SCF). Frequency domain tests are generally categorized into two main classes i.e. frequency and time smoothing algorithms. Despite the similar SCF representation of both classes, time smoothing methods are considered more efficient than frequency smoothing methods [16]. The first time-smoothing method was introduced by Gardner [17], i.e. time smoothed cyclic periodogram.

Efficient algorithms to compute SCF are defined as FFT time smoothing algorithms, i.e. FFT accumulation method (FAM) and strip spectral correlation algorithm (SSCA), are explained in [14,18]. In [16,19], the implementation models of time and frequency smoothing methods have been presented and compared. According to [14], FAM and SSCA are the two practical and efficient algorithms to detect cyclostationarity of the PU signal. For this specific reason, this research utilizes these algorithms to detect the sensed PU signal.

In order to compute SCF using FAM, SCF is represented as follows,

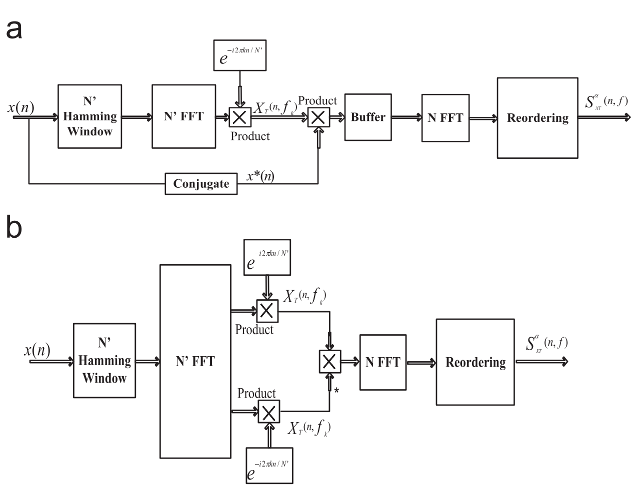

Fig. 1 (a) The implementation of SSCA [18] and (b) the implementation of FAM [16].

$$S_{X_T}^{\alpha+q\Delta\alpha}(n,f)=\sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1}\frac{1}{T}X_T\left(k,f+\frac{\alpha}{2}\right)\bullet X^{*}{}_T\left(k,f-\frac{\alpha}{2}\right)\bullet g(n-k)\bullet e^{-\frac{j2\pi kq}{N}} \quad (1)$$

where α and f are the cyclic frequency and the spectral frequency, respectively. X_T representing the complex envelope of PU sensed signal $x(t)$ and $g(n)$ is the data tapering window with width $\Delta t=NT_s$. While SCF can be estimated by using SSCA as expressed in [16],

$$S_{XT}^{\alpha+q\Delta\alpha}(n,f)=\sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1}\frac{1}{T}X_T(k,f+\alpha/2)\bullet x^{*}(k)\bullet g(n-k)\bullet e^{-\frac{j2\pi kq}{N}} \quad (2)$$

The block diagram for representing (1) and (2) is shown in Fig. 1. First, computing SCF using SSCA is addressed. Fig. 1 (a) shows the estimation of SCF using the SSCA block diagram. The main difference between FAM and SSCA is that FAM can be computed by multiplying the complex envelope with its conjugate as shown in (1). Meanwhile, in case of SSCA, it is computed by multiplying the complex envelope with the conjugate of the received signal $x^{*}(n)$, as presented in (2). The implementation of FAM is shown in Fig. 1(b).

2.2. Problem formulation

Gardner [20] has demonstrated that in order to get more reliable representation of SCF, i.e. reducing the random effects, the relation between the resolutions Δt and Δf must be as follows,

$$\Delta t\Delta f \gg 1 \quad (3)$$

The complex envelope is a function of the frequency f, thus, the number of the first FFT points is as in [14],

$$N^{'}=\frac{f_s}{\Delta f} \quad (4)$$

On the other hand, (1) and (2) are 2-D functions in terms of f and α which implies that the number of the second FFT points is also as [14],

$$N=\frac{f_s}{L\Delta\alpha} \quad (5)$$

Table 1 The computational complexity of local computing for FFT time smoothing algorithms [16].

Computation section	FAM	SSCA
Data tapering	$2N'N$	$N'N$
N'-FFT	$N'N\log_2 N'$	$\frac{N'N}{2}\log_2 N'$
Down-conversion	$2N'N$	$N'N$
Sequences multiplication	N'^2N	$N^{'}N$
N-FFT	$\frac{N'^2N}{2}\log_2 N$	$\frac{N'N}{2}\log_2 N$
Total	$N'N(4+\log_2 N'N^{N'/2})$	$N'N\left(3+\frac{1}{2}\log_2 N'N\right)$

where L is the decimation factor and $\Delta\alpha$ is the cyclic frequency resolution. Increasing the values of Δf and $\Delta\alpha$ will result in increasing of the computational complexity and reducing the random effects, or in other terms increasing the SCF reliability. In practice $L = \frac{N'}{4}$ is preferred [14,19].

In order to satisfy the reliability condition in (3), $\Delta\alpha$ and Δf must be close to zero. Thus, the number of FFT points, i.e. N' and N, will increase, as stated in (4) and (5), to infinity. This, in turn, results in increasing the number of the complex multipliers. This complexity is quantified in Table 1. The table shows that the computational complexities of FAM and SSCA are close to each other. Moreover, Fig. 2 indicates that, in case of using SSCA and FAM to compute SCF, the required number of N FFT blocks is equal to N'. Therefore, a reliable SCF computing will incur a long processing time and high power consumption which might be too costly for one CR node.

In order to reduce the complexity and to get a more reliable SCF, this paper proposes a novel scheme that distributes the workload of one CR or local computations over m cooperating CRs wirelessly, i.e. WDC. However, utilizing WDC with FFT time smoothing algorithms is expected to face various challenges. One of these key challenges is channel impact on the distributed workload over the wireless channel. The distributed workload will be affected by channel fading and noise. Therefore, the main scope of this research is to investigate the channel impact challenge on the distributed computations and propose novel schemes to overcome these challenge.

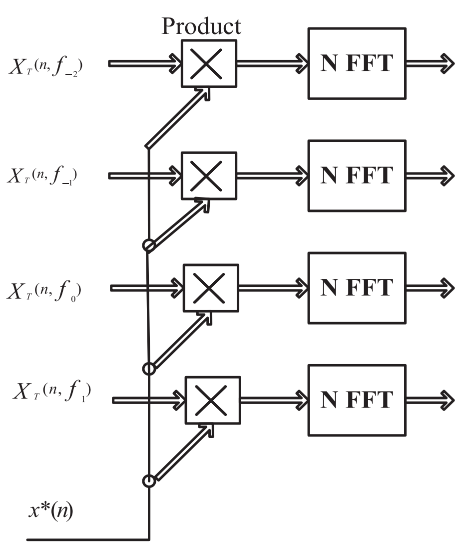

Fig. 2 The SSCA signal flow graph [13].

2.3. The proposed scheme for wirelessly the workload of FFT time smoothing algorithms

Amongst the most common spectrum sensing approaches, cyclostationary feature detection is selected to be applied in conjunction with WDC FFT time smoothing algorithms, i.e SSCA and FAM. This is due to high level of complexity of the SCF computations and WDC ability to distribute the workload of both SSCA and FAM. Even though applying WDC with cyclostationary feature detector could gain some benefits, various challenges still exist. In order to narrow the scope of the several challenges of WDC to the channel impact, the proposed method makes the following assumptions:

i. WDC system is homogeneous such that all cooperating CR nodes have the same processor type and possess identical communication and computational subsystems [3]. Thus, the distribution of the workload will be identical and uniform for each node.
ii. WDC system has a priori knowledge of the cyclic frequencies of SCF.

In order to illustrate the distribution of the workload over m slave CRs or m processing CRs, a totally distributed scheme is presented in Fig. 3(a). The scheme in Fig. 3(a) starts with sensing PU channel by SU_1. After that, each processing CR will compute its assigned workload and then transmit the workload matrices to SU_1, who wants to occupy the PU channel. Finally, SU_1 will combine the workload matrices in order to detect the channel availability. Based on Fig. 3(a), SU_1 has various roles such as electing the cooperating CRs, processing part of the workload and making decision about the combined workload matrices. The various functions that are assigned to SU_1 might increase the system drawbacks such as increasing SU_1 energy consumption and it could also face the hidden PU problem. In order to reduce these drawbacks, another scheme is described in Fig. 3(b).

The cooperating CRs of the master-slave cluster in Fig. 3(b) are composed of master CR or coordinating CR and m slave cooperating CRs. This cluster reduces SU_1 energy consumption by distributing some of SU_1 functions

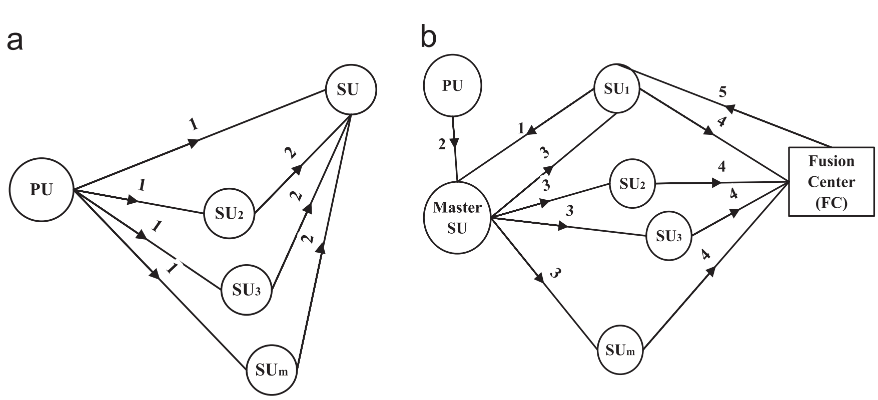

Fig. 3 Schemes for WDC method (a) Totally distributed; (b) Combined centralized and distributed.

to master CR and fusion center (FC). In Fig. 3(b), the master CR will sense the PU, gather wireless channel state information about the m cooperating CRs and select a set of CR nodes to work with. will perform task allocation algorithm to distribute the tasks among the cooperating nodes which is beyond the scope of this research. Moreover, the SU_1 role of combining the computed results and making a decision is assigned to FC. On the other hand, the hidden PU problem might be addressed by utilizing relay diversity. In Fig. 3(b), the master CR serves as a relay for the source PU. For example, if the channel between PU and SU_1 is shadowed, the transmission through master CR might be successful.

In general, the scheme in Fig. 3(b) is a combination of centralized and distributed topologies. The cooperation between CRs follows the master-slave cluster concept that is explained and utilized in [3,21]. Moreover, the idea of utilizing relay diversity was used in previous research works such as [22,23] while the approach of sending the workload matrices of m cooperating CRs to a central node was adopted in [24,25].

The steps in Fig. 3(b) are summarized as follows:

1. The SU_1, who wants to occupy the PU channel, initiates the call with the master SU.
2. The master SU will sense the PU signal [22].
3. Then, master SU will broadcast the sensed signal $x'(n)$ and will assign individual workload l_i to the m cooperating CRs, where $i = 1, 2, \ldots, m$. Due to the channel variations each CR might receive a corrupted and different versions of the input signal $x'(n)$ which can be expressed as $x_i(n) = a_i x'(n) + w_i(n)$ where a_i is a Rayleigh fading and $w_i(n)$ is AWGN. Moreover, the system is assumed homogeneous thus the workload per CR of the m slaves CR will be $l_i = l/m$ where l represents the total workload.
4. Each cooperating CR will compute N' FFT for the received $x_i(n)$. Then, it will compute the down-conversion and N FFT steps only for its assigned l_i. After that, two scenarios are considered.
   In the first scenario, each cooperating CR will encode and modulate the computed results of its workload l_i then send it to the FC for combining workload matrices, analyzing SCF and deciding about the presence of the PU. However, this scenario possesses several drawbacks, e.g. high percentage of error and overhead, due to sending large size of workload matrices through the wireless channel. In order to limit these drawbacks, another scenario is discussed.
   Instead of sending large workload matrices through the wireless channel, each cooperating CR will detect the signal cyclostationarity for its computed SCF. Then, it will select a binary flag of 1 in case of detecting cyclostationarity, otherwise it will select 0. After that, each cooperating CR will encode the flag by a suitable channel encoder and then transmit the encoded flag to the FC using BPSK. The FC will detect the cyclostationarity by ORing the received flags.
5. Finally, the FC will relay its decision to SU_1.

3. Mathematical justification of the proposed WDC with FFT time smoothing algorithms

This section verifies the mathematical viability of distributing the computational process of SCF, i.e. workload, over multiple wireless nodes. In order to prove the ability to distribute the load of one CR over m processing CRs, the SSCA is utilized to analyze SCF, the channel is considered noiseless and a random process x is received by the master PU as follows

$$x = \begin{bmatrix} x_1 \\ x_2 \\ . \\ x_i \\ . \\ x_{N'} \end{bmatrix} \tag{6}$$

$$x_i = [a_{i1} a_{i2} \ldots a_{ik} \ldots a_{iN'}] \tag{7}$$

where a_{ik} represents the vector x_i sample, $1 \le i \le N'$ and $1 \le k \le N'$.

The SSCA model in Fig. 1(a) starts with converting x to the frequency domain by computing discrete Fourier transform (DFT),

$$X = F\langle x \rangle \tag{8}$$

where $F\langle \bullet \rangle$ is the discrete Fourier transform (DFT) function. Therefore,

$$X = \begin{bmatrix} X_1 \\ X_2 \\ . \\ X_i \\ . \\ X_{N'} \end{bmatrix} \tag{9}$$

$$X_i = [A_{i1} A_{i2} \ldots A_{iN'}] \tag{10}$$

According to the proposed scheme in the previous section, the output of N' FFT in (9) will be distributed to $Y_1, Y_2, \ldots, Y_j$ as follows

$$Y_1 = \begin{bmatrix} X_1 \\ X_2 \\ . \\ . \\ . \\ X_{\frac{N'}{j}} \end{bmatrix} Y_2 = \begin{bmatrix} X_{\frac{N'}{j}+1} \\ X_{\frac{N'}{j}+2} \\ . \\ . \\ . \\ X_{2\frac{N'}{j}} \end{bmatrix} \ldots Y_j = \begin{bmatrix} X_{(N'-\frac{N'}{j})} \\ X_{(N'-\frac{N'}{j}+1)} \\ . \\ . \\ . \\ X_{N'} \end{bmatrix} \tag{11}$$

where j represents the number of the processing CRs, $2 \le j \le N'$.

Then, the next step is that each CR will compute the down-conversion of (11) for its assigned workload as follows

$$D = X \bullet E = \begin{bmatrix} Y_1 \\ Y_2 \\ . \\ . \\ . \\ Y_j \end{bmatrix} \bullet \begin{bmatrix} E_1 \\ E_2 \\ . \\ . \\ . \\ E_j \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \\ . \\ . \\ . \\ D_j \end{bmatrix} \tag{12}$$

where

$$E=\begin{bmatrix}E_1\\E_2\\.\\.\\.\\E_j\end{bmatrix}E_1=\begin{bmatrix}B_1\\B_2\\.\\.\\.\\B_{\frac{N'}{j}}\end{bmatrix}E_2=\begin{bmatrix}B_{\frac{N'}{j}+1}\\B_{\frac{N'}{j}+2}\\.\\.\\.\\B_{2\frac{N'}{j}}\end{bmatrix}\ldots E_j=\begin{bmatrix}B_{(N'-\frac{N'}{j})}\\B_{(N'-\frac{N'}{j}+1)}\\.\\.\\.\\B_{N'}\end{bmatrix},$$

$b_{ik}=e^{-\frac{j2\pi ik}{N'}}$ and the product dot (•) is declared as scalar multiplication which differs from matrices multiplication. For vector D_i, where $1\le i\le j$

$$Y_i\bullet E_i=\begin{bmatrix}X_{\frac{(i-1)N'}{j}+1}\\X_{\frac{(i-1)N'}{j}+2}\\.\\.\\.\\X_{\frac{iN'}{j}}\end{bmatrix}\bullet\begin{bmatrix}B_{\frac{(i-1)N'}{j}+1}\\B_{\frac{(i-1)N'}{j}+2}\\.\\.\\.\\B_{\frac{iN'}{j}}\end{bmatrix}=$$

$$\begin{bmatrix}A_{\left(\frac{(i-1)N'}{j}+1\right)1}A_{\left(\frac{(i-1)N'}{j}+1\right)2}\ldots A_{\left(\frac{(i-1)N'}{j}+1\right)N'}\\A_{\left(\frac{(i-1)N'}{j}+2\right)1}A_{\left(\frac{(i-1)N'}{j}+2\right)2}\ldots A_{\left(\frac{(i-1)N'}{j}+2\right)N'}\\.\\.\\.\\A_{\frac{iN'}{j}1}A_{\frac{iN'}{j}2}\ldots A_{\frac{iN'}{j}N'}\end{bmatrix}\cdot$$

$$\begin{bmatrix}b_{\left(\frac{(i-1)N'}{j}+1\right)1}b_{\left(\frac{(i-1)N'}{j}+1\right)2}\ldots b_{\left(\frac{(i-1)N'}{j}+1\right)N'}\\b_{\left(\frac{(i-1)N'}{j}+2\right)1}b_{\left(\frac{(i-1)N'}{j}+2\right)2}\ldots b_{\left(\frac{(i-1)N'}{j}+2\right)N'}\\.\\.\\.\\b_{\frac{iN'}{j}1}b_{\frac{iN'}{j}2}\ldots b_{\frac{iN'}{j}N'}\end{bmatrix}=$$

$$\begin{bmatrix}A_{\left(\frac{(i-1)N'}{j}+1\right)1}b_{\left(\frac{(i-1)N'}{j}+1\right)1}\ldots A_{\left(\frac{(i-1)N'}{j}+1\right)N'}b_{\left(\frac{(i-1)N'}{j}+1\right)N'}\\A_{\left(\frac{(i-1)N'}{j}+2\right)1}b_{\left(\frac{(i-1)N'}{j}+2\right)1}\ldots A_{\left(\frac{(i-1)N'}{j}+2\right)N'}b_{\left(\frac{(i-1)N'}{j}+2\right)N'}\\.\\.\\.\\A_{\frac{iN'}{j}1}b_{\frac{iN'}{j}1}\ldots A_{\frac{iN'}{j}N'}b_{\frac{iN'}{j}N'}\end{bmatrix}$$

$$=\begin{bmatrix}d_{\left(\frac{(i-1)N'}{j}+1\right)1}d_{\left(\frac{(i-1)N'}{j}+1\right)2}\ldots d_{\left(\frac{(i-1)N'}{j}+1\right)N'}\\d_{\left(\frac{(i-1)N'}{j}+2\right)1}d_{\left(\frac{(i-1)N'}{j}+2\right)2}\ldots d_{\left(\frac{(i-1)N'}{j}+2\right)N'}\\.\\.\\.\\d_{\frac{iN'}{j}1}d_{\frac{iN'}{j}2}\ldots d_{\frac{iN'}{j}N'}\end{bmatrix}$$

Next, the SSCA multiplies the complex envelope with x^* thus (12) is multiplied with x^* as presented

$$M=D\bullet x^*=\begin{bmatrix}D_1\\D_2\\.\\.\\.\\D_j\end{bmatrix}\bullet x^*=\begin{bmatrix}M_1\\M_2\\.\\.\\.\\M_j\end{bmatrix}\quad(13)$$

After that, according to Fig. 1(a), the SCF is computed by applying the output of (13) to a second FFT as follows

$$\begin{bmatrix}F\langle M_1\rangle\\F\langle M_2\rangle\\.\\.\\.\\F\langle M_j\rangle\end{bmatrix}=\begin{bmatrix}F\langle D_1\bullet x^*\rangle\\F\langle D_2\bullet x^*\rangle\\.\\.\\.\\F\langle D_j\bullet x^*\rangle\end{bmatrix}=\begin{bmatrix}S_1\\S_2\\.\\.\\.\\S_j\end{bmatrix}\quad(14)$$

For vector S_i, where $1\le i\le j$

$$F\langle M_i\rangle=F\langle D_i\bullet x^*\rangle$$

$$=F\left\langle\begin{bmatrix}d_{\left(\frac{(i-1)N'}{j}+1\right)1}d_{\left(\frac{(i-1)N'}{j}+1\right)2}\ldots d_{\left(\frac{(i-1)N'}{j}+1\right)N'}\\d_{\left(\frac{(i-1)N'}{j}+2\right)1}d_{\left(\frac{(i-1)N'}{j}+2\right)2}\ldots d_{\left(\frac{(i-1)N'}{j}+2\right)N'}\\.\\.\\.\\d_{\frac{iN'}{j}1}d_{\frac{iN'}{j}2}\ldots d_{\frac{iN'}{j}N'}\end{bmatrix}\bullet x^*\right\rangle=$$

$$F\left\langle\begin{bmatrix}d_{\left(\frac{(i-1)N'}{j}+1\right)1}x^*d_{\left(\frac{(i-1)N'}{j}+1\right)2}x^*\ldots d_{\left(\frac{(i-1)N'}{j}+1\right)N'}x^*\\d_{\left(\frac{(i-1)N'}{j}+2\right)1}x^*d_{\left(\frac{(i-1)N'}{j}+2\right)2}x^*\ldots d_{\left(\frac{(i-1)N'}{j}+2\right)N'}x^*\\.\\.\\.\\d_{\frac{iN'}{j}1}x^*d_{\frac{iN'}{j}2}x^*\ldots d_{\frac{iN'}{j}N'}x^*\end{bmatrix}\right\rangle$$

$$=\begin{bmatrix}F\left\langle d_{\left(\frac{(i-1)N'}{j}+1\right)1}x^*\right\rangle\ldots F\left\langle d_{\left(\frac{(i-1)N'}{j}+1\right)N'}x^*\right\rangle\\F\left\langle d_{\left(\frac{(i-1)N'}{j}+2\right)1x^*}\right\rangle\ldots F\left\langle d_{\left(\frac{(i-1)N'}{j}+2\right)N'}x^*\right\rangle\\.\\.\\.\\F\left\langle d_{\frac{iN'}{j}1}x^*\right\rangle\ldots F\left\langle d_{\frac{iN'}{j}N'}x^*\right\rangle\end{bmatrix}$$

Using the linearity property of DFT,

$$F\langle M_1\rangle=\begin{bmatrix}d_{\left(\frac{(i-1)N'}{j}+1\right)1}F\langle x^*\rangle\ldots d_{\left(\frac{(i-1)N'}{j}+1\right)N'}F\langle x^*\rangle\\d_{\left(\frac{(i-1)N'}{j}+2\right)1}F\langle x^*\rangle\ldots d_{\left(\frac{(i-1)N'}{j}+2\right)N'}F\langle x^*\rangle\\.\\.\\.\\d_{\frac{iN'}{j}1}F\langle x^*\rangle\ldots d_{\frac{iN'}{j}N'}F\langle x^*\rangle\end{bmatrix}$$

$$= \begin{bmatrix} d_{\left(\frac{(i-1)N'}{j}+1\right)1} \cdots d_{\left(\frac{(i-1)N'}{j}+1\right)N'} \\ d_{\left(\frac{(i-1)N'}{j}+2\right)1} \cdots d_{\left(\frac{(i-1)N'}{j}+2\right)N'} \\ \cdot \\ \cdot \\ \cdot \\ d_{\frac{iN'}{j}1} \cdots d_{\frac{iN'}{j}N'} \end{bmatrix} .F\langle x^* \rangle \quad (15)$$

From (15) we can conclude that the workload distribution will not effect on the final results of SCF. Thus, (14) could be written as follows

$$\begin{bmatrix} D_1 \\ D_2 \\ \cdot \\ \cdot \\ \cdot \\ D_j \end{bmatrix} \bullet F\langle x^* \rangle = S \quad (16)$$

By comparing (14) and (16), we conclude that,

$$\begin{bmatrix} S_1 \\ S_2 \\ \cdot \\ \cdot \\ \cdot \\ S_j \end{bmatrix} = S \quad (17)$$

Finally, In order to prove the viability of applying WDC with FAM mathematically, instead of multiplying (13) with x^*, it should be multiplied with the conjugate of the complex envelope while the rest of derivations follow suit.

4. Results and analysis

Due to the similarities between FAM and SSCA, herein, the investigation considers only WDC with SSCA. The benefits and limitations due to applying WDC are investigated. Moreover, because this research scope is focusing on analyzing the channel impact of applying WDC with FFT time smoothing algorithms, the accuracy of the proposed scheme is benchmarked against the conventional local computing method where all the computations are processed on only one node, i.e. $m = 1$, without any wireless distribution. Therefore, the simulation results for computing SCF by using SSCA follows the parameters in [14,26] rather than the parameters of IEEE 802.22 standard since we are only proving the applicability of the WDC concept to CR rather than applying it to a specific CR standardized technology.

In order to compare the results of WDC with local computing, this research considers the received signal by m cooperating SUs as an arbitrary random process modulated by amplitude modulation (AM) with a spectral resolution $\Delta f = 256$ where the carrier frequency f_c and sampling frequency f_s of the modulated random process are selected to be 2048 Hz and 8192 Hz, respectively. The proposed code in [26] for computing SCF by using SSCA is modified to simulate the mathematical model of applying WDC with SSCA. Then, the modified code is used to investigate the benefits, the channel effect and the accuracy of the proposed WDC method.

4.1. Benefits of applying WDC with SSCA on the computational complexity

According to the proposed scheme in Fig. 3(b), each cooperating CR computes its assigned workload l_i of N' FFT output. Thus, the required complex multipliers for local computing, that are indicated in Table 1, will be distributed among all cooperating CRs equally. The workload distribution will reduce the required complexity for each CR node as presented in Table 2.

The complexity comparison between local computing and the proposed scheme in Tables 1 and 2 is simulated using a different number of cooperating SUs and at various reliability degrees such as $\Delta\alpha = 64$ and 2. The comparison in Fig. 4 shows the complexity reduction among 50 cooperating CRs. Both figures indicate the exponential reduction of the complex multipliers while increasing the number of cooperating SUs.

Based on the results presented in Fig. 4, it is found that the best complexity reduction is achieved when the number of cooperating SUs is around $m = 4$. In addition, SCF with $\Delta\alpha = 2$ is observed to be more complex than SCF with $\Delta\alpha = 64$. The total number of the complex multipliers in case of local computing, when $m = 1$, is around 4000 and 164,000 for $\Delta\alpha$ values are equal to 64 and 2, respectively. Moreover, the half reduction of the maximum of complex multipliers for $\Delta\alpha = 64$ occurs when more than 10 cooperating CRs are processing the workload while it is achieved for $\Delta\alpha = 2$ with only 4 cooperating CRs.

Table 2 The computational complexity of WDC with FFT time smoothing algorithms.

Computation section	FAM	SSCA
Data tapering	$2N'N$	$N'N$
N'-FFT	$N'N\log_2 N'$	$\frac{N'N}{2}\log_2 N'$
Down-conversion	$\frac{2N'N}{m}$	$\frac{N'N}{m}$
Sequences multiplication	$\frac{N'^2N}{m}$	$\frac{N'N}{m}$
N-FFT	$\frac{N'^2N}{2m}\log_2 N$	$\frac{N'N}{2m}\log_2 N$
Total	$N'N\left(\left(\frac{2m+2+N'}{m}\right)+\log_2 N'N^{N'/2m}\right)$	$N'N\left(\frac{m+2}{m}+\frac{1}{2}\log_2 N'N^{1/m}\right)$

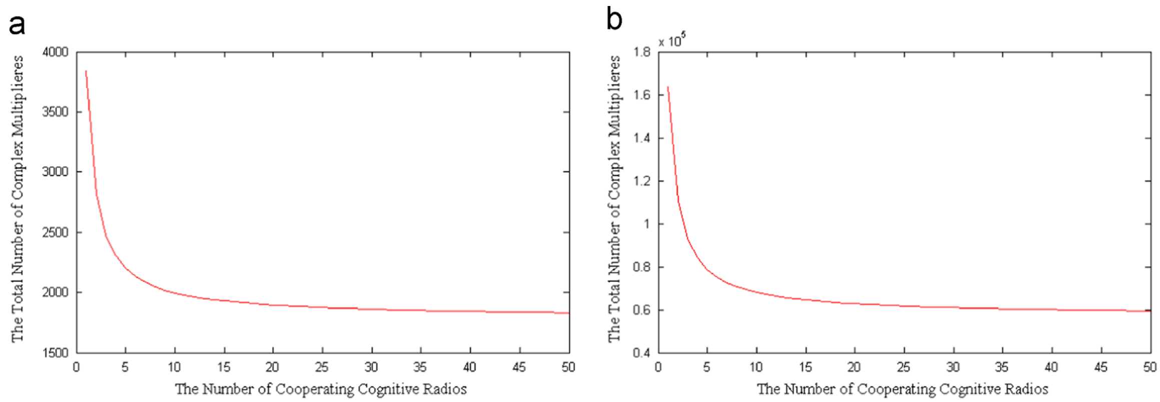

Fig. 4 The complexity comparison of local computing and WDC. (a) $\Delta\alpha = 64$; (b) $\Delta\alpha = 2$.

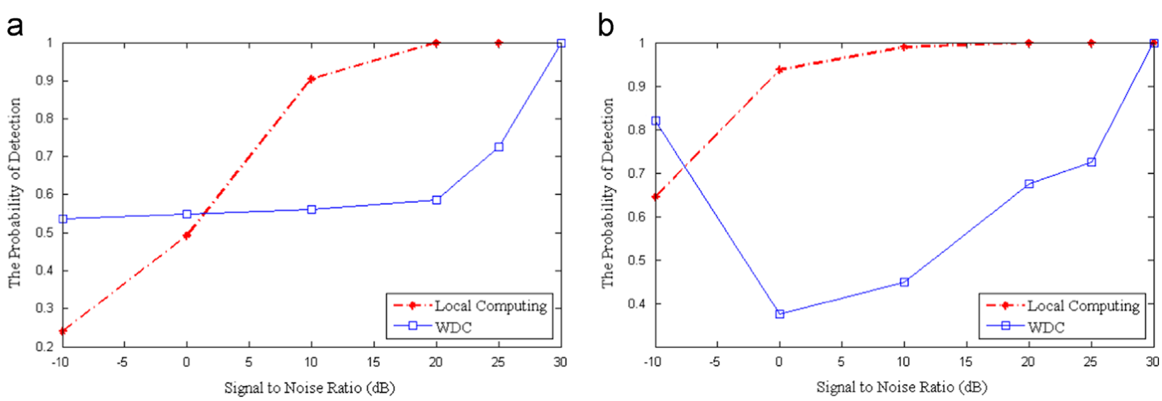

Fig. 5 Comparing P_D for local computing and WDC methods. (a) At $\Delta\alpha = 16$; (b) At $\Delta\alpha = 2$.

Therefore, we concluded that with increasing the level of reliability, by decreasing $\Delta\alpha$, a smaller number of cooperating CRs are required to reach half the maximum number of complex multipliers.

4.2. Wireless channel impacts on the proposed WDC with SSCA scheme

In case of local computing, the channel can only impact the PU's sensed signal while, in case of WDC, the channel impact varies according to the selected communication graph. Herein, the selected communication graph is shown in Fig. 3(b). Thus, the channel impact is considered between PU and m cooperating SUs, and also between the m SUs and the FC.

The channel impact on the conventional SSCA and the proposed scheme of SSCA with WDC is estimated by computing the probability of detection P_D. Both scenarios are analyzed for 4 cooperating CRs, the case that is found to achieve a satisfactory level of complexity reduction. In addition, the channel for both scenarios considers AWGN and Rayleigh fading.

4.2.1. First scenario: workload matrix size

This scenario is analyzed at different SNR values and for two reliability cases, i.e. $\Delta\alpha$=16 and 2. In the first case, when $\Delta\alpha = 16$, the size of the workload matrix processed by each cooperating CR is found to be (512,8) while in the other case, when $\Delta\alpha$=2, the matrix size is found to be (4096,8). In both cases, the workload matrices are channel encoded using a simple Reed-Solomon encoder of (255,7) and modulated using BPSK. In addition, N' is found equal to 32, the detection threshold $\Gamma = 0.5$ and the probability of false alarm $P_{FA} = 4.6566 \times 10^{-10}$.

At this value of P_{FA}, the comparison between P_D for local computing and WDC with SSCA methods at $\Delta\alpha$=16 and 2 is illustrated in Fig. 5. According to the results presented in Fig. 5, increasing the reliability of SCF enhances the accuracy only in case of local computing. However, in case of WDC, P_D performance is observed to be composed of three levels as follows

4.2.1.1. $SNR > 10$ dB. At this level, P_D in both cases of $\Delta\alpha$ is found to be equivalent. In addition, both results of P_D tend to approach 1 with increasing SNR. Based on the results in Fig. 5, an interesting conclusion is drawn, that at a specific value of SNR, changing the resolution degree or size of the workload matrices will not enhance P_D performance. Thus, after a certain value of SNR, decreasing the size of transmitted payload matrices is recommended.

4.2.1.2. $0 < SNR < 10$ dB. At this SNR range, P_D when $\Delta\alpha = 16$ is found to outperform P_D when $\Delta\alpha = 2$. The higher accuracy when $\Delta\alpha = 16$ is due to the smaller size of transmit workload matrices from the cooperating CRs to FC. However, increasing the processed workload on the four cooperating CRs by increasing SCF reliability will increase the size of the workload matrices. In this case, Reed-Solomon encoder failed in enhancing the channel accuracy, as

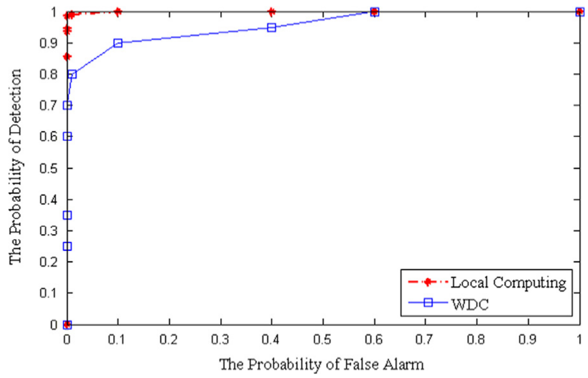

Fig. 6 The ROC at $\Delta\alpha = 16$ and $SNR = 10$ dB.

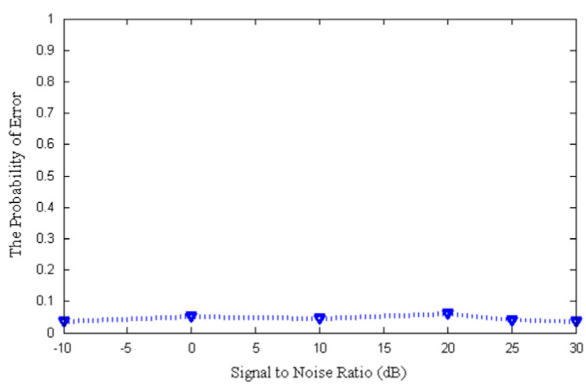

Fig. 7 The P_E for the received flags by the FC.

presented in Fig. 5(b). Thus, more sophisticated channel encoders are recommended.

4.2.1.3. SNR < 0 dB. At this level, results demonstrate that regardless of SCF resolution degree or reliability, P_D of both WDC cases are found to vary randomly at low SNRs (e.g., SCF is detecting a presence of the PU because of strong random noise fluctuations). The detection failure at low SNRs might be enhanced by selecting more sophisticated and powerful channel encoders such as turbo codes and LDPC.

In order to verify the performance of the proposed scheme of WDC with FFT time smoothing algorithms, ROC is evaluated and presented in Fig. 6. Due to the low accuracy of the proposed scheme at low SNRs and high reliability of SCF, ROC is plotted in both cases of local computing and WDC at high SNR = 10 dB and moderate levels of reliability, that is $\Delta\alpha = 16$. Fig. 6 shows that in case of local computing, P_D rapidly approaches 1 while, in case of WDC, P_D approaches 1 when $P_{FA} = 0.6$. In order to appreciate the achieved WDC performance, one needs to understand that WDC's upper performance bound is the local computing case. Hence, any further improvement to the scheme would serve to approach the local computing case at its best. This is obviously due to load sharing wireless links instead of load diversity links.

4.2.2. Secondscenario: replacing workload matrices with binary flags

In order to avoid a high percentage of errors and overhead due to sending large size of workload matrices through the wireless channel, the decision making process is done at each cooperating CR. Then, only flags of 1 s and 0 s are sent from the four cooperating CRs to the FC. These flags are encoded by repetition encoder (3,1) and then sent by BPSK. The probability of error P_E for receiving the flag incorrectly by FC is plotted in Fig. 7. The P_E is found to be same in both $\Delta\alpha$ cases and only fluctuates between 0 and 0.1.

Based on the first assumption stated in Section 2.3, the total P_D of the four cooperating CRs is expected to be the same as P_D in the case of local computing in Fig. 5. Even though the accuracy of this approach is much higher, this approach limits the generality of application due to the expected disability of other applications to make local decisions based on only part of the computations. For this application of WDC with cyclostationary feature detector, local decisions can be made by assuming a priori knowledge of α or by computing P_D using methods that do not require a prior knowledge of α.

5. Conclusion and further work

This research aimed at reducing the computational complexity of the conventional FFT time smoothing algorithms by proposing a novel scheme that performs wireless distributed computing (WDC). The proposed scheme is compared and analyzed against the conventional FFT time smoothing algorithms. The comparison found that the proposed scheme reduces the computational complexity for each processing CR. In addition, the discussion found that with increasing the reliability of the spectral correlation function (SCF), a smaller number of processing CRs are required to reach half the maximum number of complex multipliers. On the other hand, the accuracy of the proposed scheme is examined at two scenarios. In the first scenario, workload matrices were transmitted through the wireless channel. The accuracy of sending workload matrices is found to be poor at low SNR values while it is enhanced at higher SNRs. Due to the poor accuracy and the increased overhead of workload matrices, a second scenario was proposed and analyzed. Instead of sending processed workload matrices, this scenario makes a local decision at the cooperating CRs and then sends a binary flag to a fusion center (FC) on the detection of PU. Despite the enhanced accuracy of sending binary flags, this scenario limits the generality due to the disability of some applications to make local decisions.

Even though a Reed-Solomon encoder is utilized with the first scenario of the proposed scheme to combat the channel effect, its accuracy is still poor at low SNRs. Therefore, further improvement is required to enhance the accuracy of this scenario. The accuracy is expected to be improved at the FC by employing other techniques such as equalizers and more sophisticated channel encoders. Moreover, further future work is required to analyze the scheme considering IEEE 802.22 standard.

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